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EFFECTS OF SALT REMOVAL FROM UNDERGROUND DEPOSITS AND THEIR CONTROL

BY

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Chapter 2

EARTHQUAKES CAUSED BY CONVENTIONAL POTASH MINING

2.1 ROCKBURSTS CAUSE STRONG EARTH TREMORS

2.1.1 Heavy rockbursts only in German potash mining

According to statements made at international conferences (e.g., GIMM and PFORR, 1964), potash mining in Germany caused "the biggest rockbursts, the largest in the mining industry as a whole in respect to the size of the panels affected." The quoted statement refers to the 1958 rockburst at the Merkers potash mine in the German Werra potash basin; numerous publications claim that the 1958 rockburst destroyed approximately 3 km^2 of room-and-pillar mine workings in the mined-out upper potash bed and approximately 2 km^2 in the lower potash bed, see 2.4.

The powerful rockbursts caused by German potash mining are registered as earthquakes by distant seismic observatories. The strongest earthquake on German record since 1911 originated in 1975 above another potash mine of the Werra district, see 2.6.

Most of the rockbursts in German potash mining came fully unexpected; some caused numerous fatalities, others claimed no lives, but only because the mines were evacuated prior to the concentrated underground blasting which triggered the rockbursts. The reason for these regulations is the danger of huge outbursts of salt and gas, see I/4.5.1 and 2.4.1.3.

Two facts are to be considered: in Germany, potash mining began around the middle of the past century; only a few decades later, long before potash was mined in any other country, the first rockbursts/ earthquakes occurred above potash mines.

Salt and potash mining in other countries has not caused any comparable disasters.

These facts could lead to the assumption that the German potash industry paid for knowledge and experience utilized elsewhere. However, if so, one must ask why German potash mining continues to cause severe rockbursts/ earthquakes, so-called "true" rockbursts (GIMM and PFORR, 1964)?

The answer is simple: to date, German theoreticians failed to recognize the significance of stress relief creep around any excavation in salt rock; this is apparent from textbooks (SPACKELER, 1950, 1957; GIMM, 1968; DREYER, 1974a) and numerous other publications to be discussed in this chapter. Only most recently some changes in theories were noticed, see 1.2.1.1.

The principal error in hypotheses promoted over the past few decades (DREYER, since 1955; GIMM, since 1953; HÖFER, since 1958; numerous students and assistants) is explained in I/3.3.2: carnallitic potash ores, particularly pure carnallite, are believed to accumulate and store considerable elastic energy; sudden failure of carnallite pillars is believed to release the stored energy and to cause earthquakes.

The in-situ behavior of carnallite under normal mining conditions is entirely different. Under sufficient confinement, e.g., in mine pillars with adequate w/h ratios, carnallite deforms most easily by creep.

Another fundamental error in many publications is also re-emphasized here: under normal salt and potash mining conditions, stress relief creep prevents stress concentration (circumferential stresses, stress envelopes) near openings; stress relief creep zones travel ahead of advancing rooms. If and when the subsiding overburden reloads stress-relieved pillars, the pillar creep rates increase accordingly. General overburden subsidence has no detremental effects on mine pillars with adequate w/h ratios. Gradients of local near-hydrostatic stresses develop in salt and potash mine pillars between the ideal sections of the adjacent rooms. Superficial spalling off pillars indicates safe pillar behavior as the pillar core is deforming by creep which excludes the hazard of sudden failure, see I/3.3.2.

With reference to observations and creep measurements in German potash mines, theoreticians were repeatedly urged to reconsider their hypotheses regarding the in-situ behavior of carnallite (BAAR, 1953c, 1954d, 1958, particularly 1959b, pp. 170-173). Some were puzzled with the spectacular surface damage caused by the first rockburst in the Werra potash mining district in 1953; according to questionable hypotheses developed in coal mining, see 2.1.2.4, rockbursts could not occur in that mining district.

In fact, however, the 1953 event represents a textbook example of sudden tensile failure of an elastic overburden formation which was not adequately supported because of stress relief creep of carnallite pillars. The mechanism is dealt with in 2.3; the mechanism of other powerful rockbursts above German potash mines is similar.

Elastic overburden formations similar to those above the Zechstein salt sequences of Germany may be present in other salt and/or potash mining areas. For this reason the mechanics of the powerful rockbursts/earthquakes above potash mines in Germany are to be shown in detail.

Controversies regarding the mechanism of the rockbursts/earthquakes above German potash mines have been going on for nearly a century.

This writer became involved in investigations into the causes of rockbursts and pillar failures during the early 1940's while working as an assistant for Professor Dr. W. Schmidt, Faculty of Mining and Metallurgy, Technical University of Berlin. The controversies flared up after mass accidents in German potash mines in 1951; some writers speculated that cosmic events caused the 1951 disasters and similar previous events in various potash mines. Such publications cannot be left undiscussed as they attempt to hide consequences of the application of dangerous hypotheses. The 1951 events and similar previous events listed in German rockburst statistics are not classified as rockbursts and dealt with in Chapter 3.

2.1.2 Definitions and hypotheses need clarification

2.1.2.1 Elasticity theory used in rockburst interpretations

The ISRM Commission on Terminology (1975) defines rockbursts as "sudden explosive-like release of energy due to the failure of a brittle rock of high strength." Brittle fracture is defined as "sudden failure with complete loss of cohesion across a plane."

These definitions cover the mechanism of the powerful rockbursts above German potash mines, i.e., the sudden tensile failure of an elastic overburden formation due to inadequate support by mine pillars. The extensive in-situ creep of salt rocks disallows the classification of salt rock as brittle rock of high strength. As stated before, the principal error in hypotheses promoted over the past few decades by some writers is the belief that salt-rock pillars, particularly pure carnallite, accumulate and store considerable elastic energy whose release due to brittle pillar failure is believed to constitute "true" rockbursts.

The same ISRM Commission (1975) defines spalling as "a) longitudinal splitting in uniaxial compression, (b) breaking-off of plate-like pieces from a free rock surface." This definition ignores the most common cause of spalling in deep salt and potash mines, i.e., the separation of spalls (slabs) from non-ideal room sections. After rapid stress relief creep has eliminated stress differences which cause plastic deformation (creep), near-surface spalls (slabs) behave elastically and are sheared off the ideal "active" section, see Figure 1 - 1. Surficial spalling indicates safe performance of pillars with adequate w/h ratios.

Spalling due to rapid stress relief creep frequently takes place in a violent manner, particularly in cases where abutment loads are superimposed on remnant pillars in deep salt and potash mines. Such spalling satisfies the rockburst definition proposed by COATES (1967): "the violent failure of rock, when on a scale sufficient to endanger material or personnel." Violent spalling off the ideal cross-section of openings, see Fig. 1 - 1, made it necessary to introduce stress-relief mining methods in the deep Canadian potash mines. However, such spalling cannot be compared with "longitudinal splitting in uniaxial compression."

Plate-like pieces frequently break off roof and floor of mine openings in well-stratified salt rock due to buckling; separation of salt beds is made possible by interlayers of what is often called "clay".

The definition of buckling by the ISRM Commission (1975) is not applicable to such breaking-off of plate-like pieces of salt beds; buckling is defined as "instability of a column or a plate under sufficient high load due to sudden deflection of the structure."

The term "buckling" as used in this text means the deflection of salt beds which separate from roof and/or floor of excavations due to lateral forces generated by creep into mine openings. Such buckling is not a sudden process, it rather depends on creep rates under given conditions. It is re-emphasized that stress relief creep in deep potash mines is the primary cause of buckling of roof and/or floor strata in flat-lying deposits; frequently, buckling is caused only by stress relief creep.

Instead of paying due attention to stress relief creep, many writers use the theory of elasticity to account for stress concentrations around mine openings in salt. Fig. 2-1 demonstrates the theory (OBERT 1967, Fig. 21).

The writer (l.c., pp. 41-43) elaborates as follows: "the total load on a sufficiently large underground area must remain unchanged even if an opening or openings are mined in the area. Consider an opening (tunnel

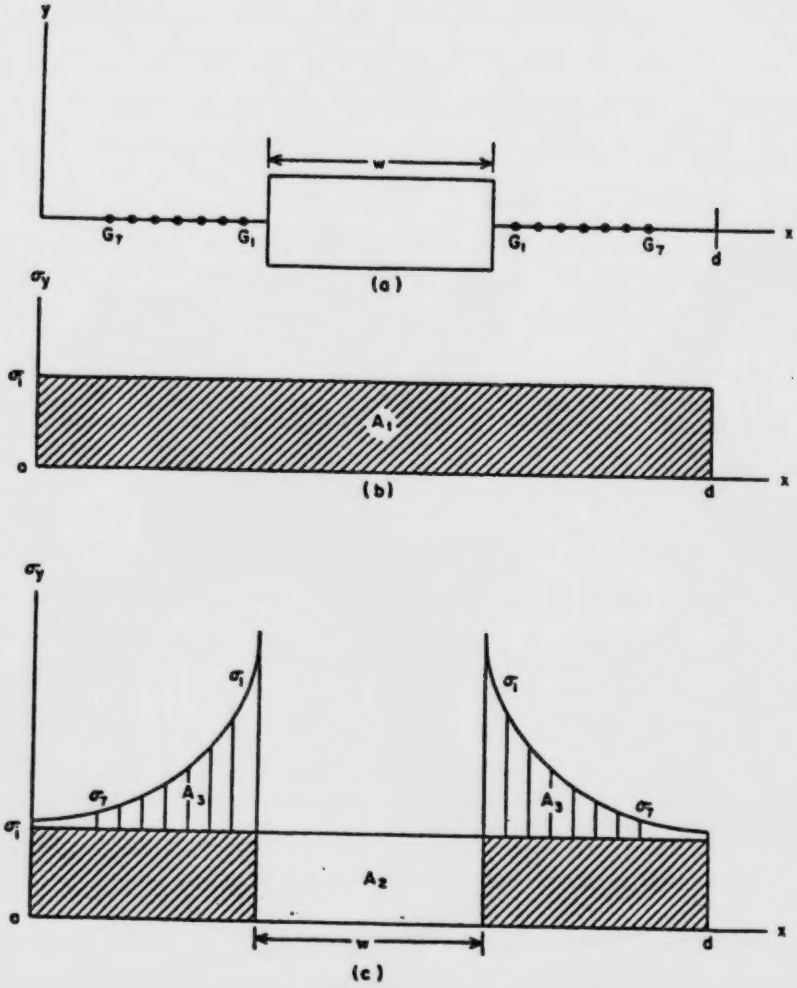


Fig. 2-1: Static equilibrium of stress near opening in elastic rock (after OBERT, 1967; Fig. 21), see text for explanation.

or drift) of width w driven through a body at right angles to the xy plane, Fig. 2-1a. Assume that before the opening is driven the vertical stress σ_y has the pre-existing or initial value σ_i . To analyze this two-dimensional problem consider a slice parallel to the xy plane, which has the width d and the thickness unity. Before the opening is driven, the total force in the y-direction acting on the horizontal plane through o-x is equal to $\int_0^d \sigma_i \, dx = \sigma_i d$, which is represented by area A_1, Fig. 2-1b. To satisfy the requirement of static equilibrium for the forces acting in the y-direction it is necessary that the total force remain equal to $\sigma_i d$ after the opening is created. Driving an opening of width w through the rock removes a force $\sigma_i w$ (area A_2, Fig. 2-1c). To satisfy the condition of static equilibrium along o-d a force equal to $\sigma_i w$ must now be added to the rock at the sides of the opening, that is, $\sigma_i w = A_2 = 2A_3$. If the rock is reasonably elastic, this force will be distributed more or less as indicated by the curves specified by the ordinates $\sigma_1 - \sigma_7$, Fig. 2-1c."

Particular emphasis is to be placed on the prerequisites for the application of the quoted theory: the rock must exibit elastic behavior, and a sufficiently large area must be taken into consideration, i.e., mined-out areas must have reached certain spans. As long as spans are insufficient, static equilibrium near the surface may be achieved by plate-like behavior of elastic overburden formations. In such cases overburden loads are transferred to abutments and supported in very large areas until excess tension causes failure of the elastic plates. If such failure takes place in a violent manner, it results in sudden additional loading of pillars, see 2.1.2.3.

2.1.2.2 Pressure-dome or stress-arch concepts

Some hypotheses promoted over the past decades to interpret the mechanics of rockbursts in German potash mining resemble the pressure-dome hypothesis developed in South Africa.

According to BLAKE (1972), "the pressure-dome theory used stress concentrations in the vicinity of mine openings to account for rock bursts. The rock fractures when stress in this concentrated zone exceeds the strength of the rock. If the rock is brittle, the fracturing process may be violent and result in a small rock burst. As these fractures progress outward from an excavation, a dome-like area of fractured rock develops.

This zone is destressed by virtue of being fractured, but a high-stress zone exists around the dome in the unfractured rock. Large bursts occur when the load supported by the dome is concentrated in pillars or remnants, and when two or more domes meet, resulting in a further stress concentration. Stope closure results as a consequence of the fracturing of rock within a dome."

Fig. 2-2 (DENKHAUS, 1958) demonstrates the pressure-dome theory. The writer (l.c.,p.20) emphasizes that the fractures generally develop parallel to the vertical faces around nearly all mine openings; the excavations are surrounded by a zone of fractured ground; at great depths, the zone of fractured ground may not extend to the surface.

"While there is no doubt as to the existence of zones of fractured ground around excavations, little is known about their form and their extent. Also, it is not known if there is a sharp limit between solid and fractured ground, or if there is a transition zone."

The lines of thrust of Fig. 2-2 indicate secondary arches supported at the advancing face and at some distance from the face. The writer emphasizes that the fractured ground inside pressure-domes is protected against overburden load, i.e., pressure domes are considered as stable support elements, transferring the overburden load to abutments around mined-out areas.

The pressure-dome theory resembles hypotheses which postulate stable stress arches, stress envelopes, or circumferential stress concentrations around mined excavations in salt rocks. Such hypotheses are promoted in numerous publications dealing with the mechanism of rockbursts in German potash mining, although salt rocks do not meet the most important prerequisite of elastic behavior.

2.1.2.3 Pillar failure hypotheses

Many recent publications consider pillar failure in room-and-pillar mines as the only possible rockburst mechanism. The following review is based on Salamon (1974) who fails to mention the pressure-dome theory and similar hypotheses; quotations are preferred in view of the controversial nature of the subject matter.

"A major hazard arising out of deep-level mining of tabular deposits is the occurrence of rockbursts, which may be defined as '...damage to underground workings caused by the uncontrolled disruption of rock

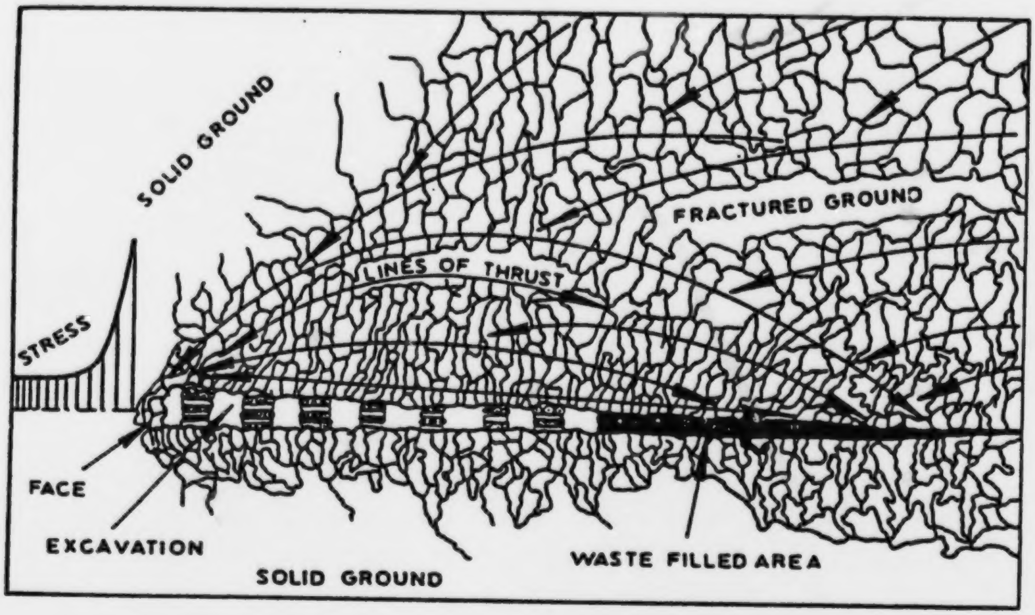


Fig. 2-2: Sketch showing pressure-dome theory (after DENKHAUS, 1958; Fig. 2), vertical cross-section on strike through stoping excavation and fracture zone.

associated with a violent release of energy...'. The term rockburst has been used to describe phenomena ranging from the expulsion of small fragments of rock from the sidewall of an excavation to the collapse of many square kilometres of pillared areas. Little is to be gained here from a lengthy discussion of the meaning of the various other terms used in the literature to describe such violent events in mines... The attention is focused on occurrences which might cause major interruptions in mining operations."

Roof falls and spalling off pillars in salt and potash mines frequently cause major interruptions; as a matter of fact, roof falls in developing Canadian potash mines made it necessary to abandon large areas, and to redevelop the mines, using stress relief principles, see I/5.2.

In this text, roof falls and spalling off pillars are not considered as rockbursts. Large-scale roof falls, listed as rockbursts in German statistics, are dealt with in Chapter 3.

SALAMON (l.c., p.1083) emphasizes "that a very large amount of kinetic energy can be generated by the failure of pillars when mining is done at great depths." However, to use his own words, little is to be gained here from a lengthy discussion of pillar failure as the powerful rockbursts above German potash mines are not related to pillar failure. The pillars perform as is to be expected. The problem is that some theoreticians expect the pillars to represent stable support elements.

According to the writer, "the terms 'stable' and 'unstable' are often misused when applied to underground cavities. Frequently they imply merely that rock failure may or may not occur. In the course of mining a part of the rock surrounding the excavation often fractures. Mining engineers, and to a much lesser extent civil engineers, have learned to accept and to control the fractured rock. Problems arise when some unexpected failure takes place. This unexpected event may take the form of a rockburst, a sudden fall of roof, or sudden failure of pillars, etc.. In these instances, a previously stable structure, for no apparent reason, suddenly becomes unstable."

"Instances of sudden failure of pillar workings are well known in mining literature. SPACKELER et al. (1960) give an account of a major failure which took place in one of the German potash mines in 1958." (This writers remark: no pillar failure involved, see 2.4). TINCELIN and SINOU (1960) describe two distinct types of pillar failure which have been observed in the iron ore mines of Lorraine:

(a) slow, progressive collapse which leads, after some delay, to surface damage, and

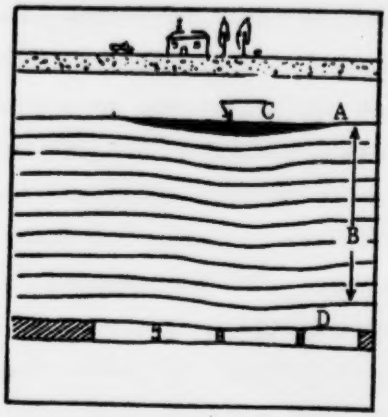
(b) sudden, violent collapse which causes immediate surface damage and often fatal accidents due mainly to airblast.

They devote their paper to an attempt of providing an explanation of the second type of collapse of which, according to them, seven have occurred since the beginning of the century."

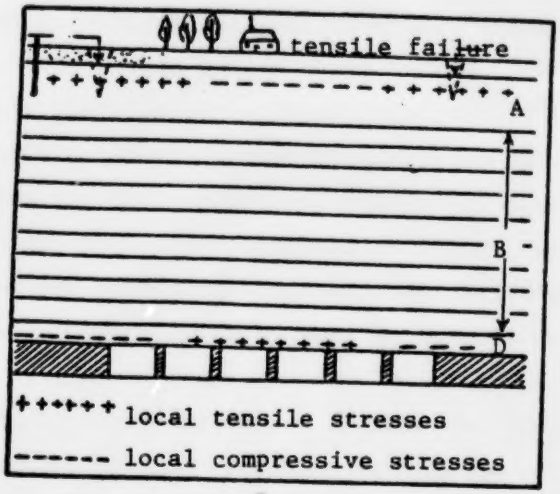
"BRYAN et al. (1964) describe a sudden and disastrous pillar collapse in a South African colliery in 1960. Some 2½ km^2 of pillared area collpased with the loss of 437 lives. Several other pillar failures are known to have happened in South African coal mines but no record of other violent failure exist. It must, therefore, be accepted that classification of pillar collapses by TINCELIN and SINOU into the earlier mentioned types is justified."

SALAMON (1974) ignores the main point stressed by TINCELIN and SINOU (1960): sudden, violent collapse with immediate surface damage took place because of tensile failure of a near-surface limestone formation as shown in Fig. 2-3; the mechanism is explained as follows (translated from the German text, l.c., p.7): the weak, well-stratified overburden strata commence to bend due to pillar compression as indicated; in this way the cavity C can develop underneath the rigid stratum A near the surface. As soon as the span of the cavity becomes large enough, the rigid near-surface stratum suffers tensile failure and collapses suddenly onto the bended floor strata of the cavity; this impact causes instantaneous pillar failure and collapse of the whole overburden.

The writers show photographs of surface fractures up to 1 m wide, emphasizing that such fractures form above the edges of collapsed areas. The surface fractures resemble those caused by the first powerful rockburst in the Werra potash mining district in 1953, which represents a textbook example of sudden tensile failure of an elastic overburden formation, as stated previously (BAAR, 1959b). In this regard, the analogy between the heavy rockbursts above German potash mines and those above the Lorraine mines, type (b) as quoted above, appears to be perfect. The pillar behavior, of course, is entirely different in the two types of



A


tensile failure
A
B
D
++++++ local tensile stresses
------ local compressive stresses

B

Fig. 2-3: Rockburst caused by sudden tensile failure of near-surface limestone formation above iron ore mines, Lorraine, (after TINCELIN and SINOU, 1960; Abb.3 and 3 bis),

A - thick, rigid stratum
B - soft strata subsiding over workings
C - cavity formed below 'A'.
D - thin, rigid stratum in the roof of the ore.

of mines, as shown in more detail in 2.3.

The force-convergence characteristics of salt-rock pillars differ considerably from those shown by SALAMON (1974) with reference to WAGNER (1973, private communication, apparently referring to German textbooks on salt and potash mining). The deformation characteristics of salt-rock pillars cannot be improved significantly "by providing some lateral confinement to the pillars, for example,...by employing hydraulic back-filling around them. The last method is very effective in thick horizontal seams, even if the fill is not in contact with the roof. This is so because the consolidated fill effectively resists the lateral loosening, which is considerable in the failing regime of the pillars."

Such expectations proved extremely dangerous in salt and potash mining. As a matter of fact, some of the powerful rockbursts above German potash mines were caused by the practical application of the quoted postulates, see 2.2.

SALAMON (l.c., p.1046) sees " a further indirect danger arising from a competent, high-modulus roof. If the modulus of the roof strata is high then the progress of failure (of pillars) is slower, because the rate of increase in convergence is decreased. In such instances the obvious signs of approaching pillar failure such as scaling and spalling, might be less obvious or even absent, so that no timely warning of the impending disaster will be visible."

These postulates resemble those promoted by various German writers; they must not be applied to salt-rock pillars as scaling and spalling may be caused by stress-relief creep only. In such cases spalling off the ideal cross-section of rooms indicates safe behavior of pillars with adequate w/h ratios rather than an impending disaster.

An impending rockburst disaster due to tensile failure of a competent overburden formation is indicated by missing surface subsidence in cases where room-and-pillar panels exceed certain spans, see Chapter 7.

The following continuation of the preceding quotation is equally questionable:

"It is of considerable interest that TINCELIN and SINOU (1960), although postulating an erroneous mechanism to explain sudden collapses, did arrive at conclusions which can be accepted to be correct, at least qualitatively, even some 13 years after the presentation of their paper.

They recommended, to use a somewhat paraphrased version of their conclusion, that to avoid sudden collapses (they refer to rockbursts) either the pillars must be able to withstand the maximum pressure corresponding to the pillar layout (conventional method of design) or the workings must be subdivided into panels the spans of which must be less than some critical value. The panels must be separated from each other by stabilizing pillars" as shown in Fig. 2-4.

The separation of room-and-pillar panels by stabilizing pillars (often called barrier pillars) can be extremely dangerous in salt and potash mining. The subject matter is dealt with in some detail in I/5.3 and I/5.4; the potential danger is particularly serious under geological conditions where non-salt evaporites in the proximity of mine workings contain gases and/or brines.

As mentioned in 2.1.1, published controversies regarding the feasibility of barrier pillars in German potash mines flared up after several mass accidents in 1951. Some writers called for stabilizing barrier pillars. At that time, the mine safety authority could be convinced of the potential danger (BAAR, 1953c, 1954a), and the barrier-pillar concept was dropped.

However, the dangerous concept was re-introduced (GIMM and PFORR, 1961), apparently due to inadequate comparison of room-and-pillar mining of potash beds with longwall mining of coal seams, see 2.5

For room-and-pillar mining, SALAMON (1974, p.1021) postulates w/h ratios "exceeding 15, or perhaps even 20, to ensure that pillars cannot fail. Another mode of failure of a partial extration layout is a failure of the 'foundation' of the pillars, that is, failure in the rock either below or above the pillars."

These postulates apparently consider the lateral creep of salt rocks in roof and/or floor of pillars and abutment zones as failure, demonstrating that civil engineering principles must not be applied in the design of excavations in salt deposits.

For panel-and-pillar layouts SALAMON (l.c., p. 1050) reduces the postulated w/h ratios of stabilizing pillars to at least ten; however a "perfectly stable layout" is postulated again.

Such postulates are not applicable in salt and potash mining where stress relief creep into excavations is inevitable; perfectly stable openings simply cannot be designed, no matter how often some theoreticians

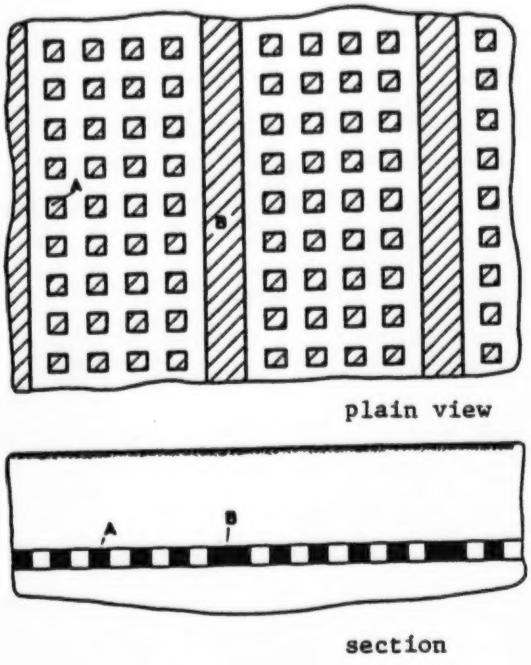


Fig. 2-4: Panel and pillar design after(SALAMON, 1974; Fig. 6.8.10)

A - yielding pillars (panel pillars)
B - stabilizing pillars (barrier pillars)

claim so, see I/5.4.

SALAMON (l.c., p.998) refers to "a critical situation of an unsupported tunnel in brittle rock, i.e., the rock is in brittle state ... in which the ability of the rock to resist load decreases with increasing deformation", see Fig. 2-5.

Such postulates are derived from elasticity theories, see Fig. 2-1.

Many writers promote similar postulates for openings in salt rock. However, elasto-plastic rock, specifically salt rock, exhibits elastic behavior only until the limit of elastic behavior, the creep limit is reached; if and when that threshold is surpassed, creep (plastic behavior) is inevitable.

2.1.2.4 Rockburst hypotheses (coal mining) not applicable in potash mining

In German publications which deal with the rockbursts/earthquakes in potash mining, frequent references are made to NIEMCZYK (1949). The writer refers exclusively to rockburst situations in coal mining and considers the failure of elastic roof beds as rockbursts.

References to NIEMCZYK (1949) led to questionable hypotheses as the fundamental difference between longwall extraction of coal seams and room-and-pillar mining of potash beds was ignored. The geometrical rockburst situations according to the reference publication are presented for future reference and discussion (after GIMM and PFORR, 1961, p. 100):

A. Only one seam mined.

Case 1: too many roadways.
Case 2: abutment load on remnant pillars.
Case 3: abutment load near longwall faces.

B. . Two or more seams mined.

Case 4: additional load due to overlying or underlying faces.
Case 5: additional load due to overlying or underlying remnants.

BRÄUNER (1977) presents virtually identical geometrical situations in a different order as follows:

> "I: Face commencing. The seam is placed under increasing load as long as the main roof has not yet fallen."

Apparently, this is case 3. However, in salt and potash mining, the main roof strata must not be allowed to fall; the limiting surface subsidence, see Fig. 7-1, must be achieved without fracturing and fall of the main roof in order to prevent dangerous water inflow into the mine.

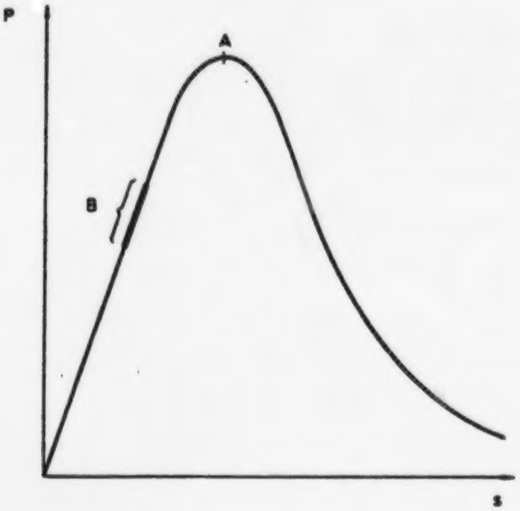


Fig. 2-5: Contrast between pillar strength (A) and the estimated load acting on the pillar (Zone B), if the safety factor is about 1.6 (from SALAMON, 1974; Fig. 6.8.11)

> "II: Corner of a seam; in the course of working adjacent to a former panel, the pressure zone in front of the face crosses the pressure zone of the old panel. The seam may come under particularly heavy stress in the area of intersection, about 40 metres wide."

This situation is the logical consequence of case 3. However, the width of the area of intersection depends on the widths of the two overlapping abutment load zones, i.e., on the behavior of the subsiding overburden strata. This behavior may differ in two horizontal directions, depending on the presence of faults and similar zones of weakness which tend to follow certain directions in any particular mining area. Apparently some writers recently learned this lesson, see 1.2.1.1.

In room-and-pillar mining where pillars support the full overburden load at all times, the corner-of-a-seam effect is negligible as no "heavy-stress" abutment zones exist in front of advancing faces.

In salt and potash mining with yielding pillars, the corner-of-a-seam effect differs from the quoted situation II in coal mining: near the corner of a remnant pillar, horizontal creep into mine openings takes place in two directions rather than in one direction as is the case at some distance from the corner.

As a consequence, the detrimental effects of creep on roof and/or floor strata are greatly reduced. Near the corner of any pillar, there is less danger of roof and/or floor failure due to horizontal deformation. The same holds true for spalling off opening walls. The reader is referred to published measurement data summarized in Chapter 1.

> "III: Formation of a pillar...due to workings in the same seam. The pillar no longer has the load bearing capacity of an unworked zone in front of the face...
>
> Situation III has been found by experience to be the most dangerous; it occurs in the majority of severe rockbursts."

This is case 2. However, the writer refers to an entirely different failure process. The most important feature of what the writer calls rockbursts "is almost always a thrust in the coal occurring with great force. However, there are important variations in the extent of this thrust, the mass of coal affected, and conseuqnetly the degree of destruction in the mine workings. We can draw up an almost continuous scale ranging from severe rockbursts which thrust the seam several metres forward and completely fill a roadway over a distance of 100 metres, down to very slight rockbursts which only displace a few props to a small extent. But even slight rockbursts are dangerous, since it is always possible that work may be in progress at the place concerned. In any case it is not possible to predict how severe a rockburst will be."

The preceding quotation makes it clear that the writer refers to outbursts of coal and gas rather than to rockbursts as defined in this text.

The writer advocates "drilling into pressure concentrations in the seam to set off relief mechanism varying greatly in magnitude." It is emphasized here that the technology of relief drilling in coal seams was developed in Hungary; interested readers are referred to publications (e.g., FREIBERGER FORSCHUNGSH. A 304, 1964).

Relief drilling is not feasible in salt rocks where gases are occluded in or between crystals, see I/4.5. However, small outbursts of salt and gas can be initiated at safe distances from advancing faces to prevent huge outbursts which cannot be controlled, see 2.4.

In the following quotation BRÄUNER (1977) apparently refers to different types of rockbursts:

"The most important geological precondition for the risk of rockbursts is a thick bed in the roof, consisting usually of sandstone, more rarely thick bedded shale, but not necessarily lying directly on the seam. In particular it has been found that, as a precondition for the danger of rockbursts, such beds require to be at least 5 m thick and not more than 10 metres above the seam."

Similar postulates by NIEMCZYK (1949) are frequently cited in publications dealing with rockbursts in German potash mining, as mentioned previously. BRÄUNER (1977) elaborates as follows: "Part of the energy released in a rockburst generates oscillations which are felt as a more or less powerful shock to the rock strata, usually up to the surface. Such shocks are usually also noted in the reports of seismographic stations. But the strength of such shocks gives no indication of the immediate effects of the rockburst. Even with a severe shock there is frequently no damage underground, so that there may therefore be other reasons for shocks with the source near the surface. Shocks should therefore not be equated with rockbursts."

The reader is referred to Fig. 2-3, and to the related discussion; the most powerful rockbursts experienced in the Werra potash mining district are caused by tensile failure of a near-surface sandstone formation; the immediate roof of the mines consists of more than 100 m of salt sequences which suffer no damage. This is to be shown in detail. In many mining districts, room-and-pillar mining of potash beds is not endangered by remnant pillars, provided that rooms and pillars are adequately designed and that smooth, gradual surface subsidence can be initiated. However, as long as bridging formations prevent overburden subsidence, remnant pillars are extremely dangerous; this is to be shown by case histories.

"IV: Ribs in other seams. The working (face or roadway) is subjected to the abutment pressure from higher or lower seam edges. The pressure becomes particularly high when these edges form a residual pillar or seam corner."

This is a combination of cases 4 and 5. BRÄUNER (1977) apparently refers to situations as shown by EVERLING and JACOBI (1977) who calculate stress concentrations on the assumption of elastic behavior; the latter writers comment on the effects of "residual pillars" which are termed remnant pillars, safety pillars, or barrier pillars in this text:

"In many coalfields throughout the world the practice is to leave solid pillars of coal between the panels and drive the roads in these pillars. The method is intended to protect the roads from the pressure exerted at the edges of neighbouring workings...Calculations have shown that "protective pillars" would have to be 100 m wide at each side of the road at a depth of 800 m to keep the rise in pressure caused by mining on both sides below 50%."

"50-m pillars on both sides only reduce the pressure to 2.5 times the pressure of the overlying strata. At the pillar edge, the pressure can reach as much as 6 times the overlying strata pressure and has a damaging effect on the face end in these locations." These figures differ considerably from those presented by EVERLING (1974, fig.3, p. 1445).

It may be questioned that the use of elasticity theories for rock masses with non-elastic behavior can provide reliable solutions. In any case of relatively fast overburden subsidence, the calculated "iso-pressure" lines - Fig. 2-6 is shown as an example - would disappear when the limiting subisdence is reached, see Chapter 7. However, it is appreciated

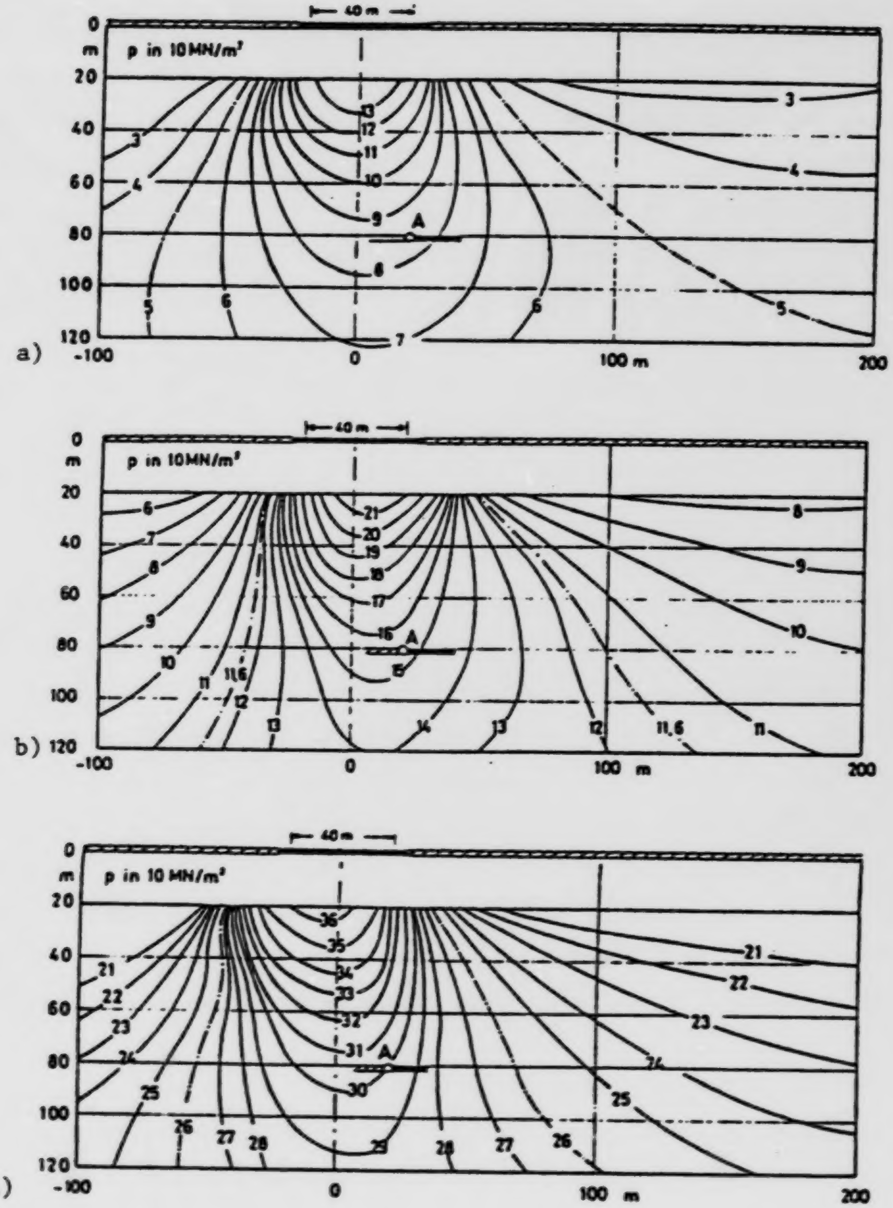


Fig. 2-6: Iso-pressure lines (p) on the standing wall of a gate-road under a residual pillar parallel to it (from EVERLING and JACOBI, 1977; Fig. 11)

a) pressure on the wall of the machine stable (road carried with face)
b) pressure 300 m behind the first face
c) pressure ahead of the second face (abscissa and ordinate: distance in m).

that the writers fully confirm qualitative assessments of the negative effects of so-called barrier pillars, "protective pillars" or entry safety pillars (BAAR, 1954a; 1959b, with reference to papers presented by VENTER and STASSEN, and by SUDOPLATOW and BARANOWSKI). These matters are to be discussed in detail on the basis of case histories.

"V: Additional roadways. This concerns the stress increase due to adjacent roadways in the seam or in the rock."

This apparently is case 1 (too many roadways). BRÄUNER (1977) concludes his description of geometrical rockburst conditions as follows:

"In general, various combinations may occur, and this is the case with many rockbursts, but it is usually possible to recognize which is the prevailing influence. The following figures are quoted for comparison: in 40 working points with rockbursts, 7 corresponded to situation I, 6 to situation II, 17 to situation III, 7 to situation IV, and 3 were a combination of situation IV and V. Quantitative information on the safety aspects of these geometrical situations are given in the official instructions."

The "quantitative information" is based on the assumption of elastic behavior and cannot be reliable in cases of inelastic behavior, as particularly stressed by WILSON (1977) whose conclusion is quoted as follows:

"Soil mechanics has been used extensively by civil engineers for many years; hard-rock mechanics based on the theories of elasticity can explain many of the facts observed in the mining of strong rocks. Recognition of an intermediate state, soft rock mechanics, is required to explain much of the phenomena found when mining in weak rock such as the coal measures."

"Soft rocks fail around excavations, but their internal friction allows the build-up of substantial load bearing capability within a comparatively short distance. This yield zone confines and gives strength to the unfailed rock beyond."

"By approximating the laws of behavior of failed rock, mathematical formulae can be developed to explain the facts as observed underground. So far the formulae can only be considered as approximate, and relate only to stress distribution, but their judicious application can be of use. Much more work is required on the subject, especially in relating the stress field to movement of rock."

These conclusions are noteworthy indeed, since many writers do not make any differentiation between the terms "yield zone" and "creep zone": "in weak rock, if a very weak support is used, the yield zone may extent to 70 m (230 ft) from the roadway edge at a depth of 1000 m (3300 ft)."

Regarding yield zones alongside wide excavations, the writer states that "no general solution is yet available."

"Beyond the yield/elastic boundary, the stress concentration will decay until it eventually reaches cover load. Whether this decay will follow a power law, hyperbolic law or exponential law is not yet known."

These statements should be borne in mind, particularly in view of the in-situ measurements presented by BIELENSTEIN et al. (1977). The writers report and document "substantial plastic deformation of the coal, particularly floor heave, caused by the pressure of up to 1800 feet (550 m) of overburden.

The following facts appear particularly significant: "Underground mining... is carried out by the room-and-pillar method. Individual panels are usually developed with a three-entry system along strike on the down-dip side of the panel. Rooms are developed in the panel and pillars are extracted on retreat and down the dip. Continuous miners are used to cut rooms 18 feet (5.5 m) wide by 8 - 10 feet (2.4. to 3 m), the height is dependent on the area being mined."

The extraction method excludes yielding due to blasting, so the results of the measurements allow better comparisons with results obtained in potash mines where the openings are also cut with boring machines. Readers who are inclined to question extensive plastic deformations in room-and-pillar mining of coal and salt/potash are urged to study the measurement results. Some results could be quantified. However, the measuring program was not yet completed at the time of publication, so the final affects of undermining and undercutting a beltway "are not entirely known."

The use of the term 'plastic deformation' for the measured inelastic displacements might be questioned because of the composition of the coal-bearing formation "which comprises interbedded sandstones, shales, siltstones and coal. Individual rock units are discontinuous and detailed correlation is almost impossible although for short distances the coal seams can be used as marker horizons."

Comparable rock units form the roof strata of many flat-lying salt and potash deposits. In cases where the strata are heavily fractured, such rock masses exhibit what many writers term pseudo-plastic behavior. Some details of texture and stratification are presented in I/2.

2.1.3 Statistics on rockbursts in German potash mining.

Many published data on rockbursts above German potash mines are not reliable, see Table 2-I.

Some erroneous data found in recent publications apparently are due to printing errors which escaped correction in older publications. Some errors (DREYER, 1974a) could not be traced to their origin as the writer either refers to unpublished papers or fails to indicate his sources. Details are presented in the respective following sections.

As emphasized in 2.1.1, tensile failures of elastic overburden formations represent the "true" rockbursts above German potash mines. Two formations are to be considered, the so-called Main Anhydrite and the Bunter Sandstone.

The Main Anhydrite above the Stassfurt potash bed has virtually the same composition throughout the Zechstein basin. However, it is severely fractured at many locations as shown in I/2. Heavy fracturing in salt domes and steep anticlines (Figs. I/2-31, I/2-34) eliminated the danger of rockbursts due to failure of the Main Anhydrite, as shown in the respective following case histories.

From a rock-mechanical point of view, the Bunter Sandstone formation above the Zechstein salt sequences also has virtually the same composition throughout the Zechstein basin, from England to Poland. In comparison with the Main Anhydrite fracturing is less intensive. Upper portions of the Bunter Sandstone with original thicknesses of approximately 500 m were eroded above some potash mines where rockbursts occurred.

Many German writers are misled by the erroneous postulate that, as a pre-condition for rockbursts, a thick, elastic roof must exist not more than 10 metres above the extracted potash bed, see 2.1.2.4. This is the apparent reason why SPACKELER et al. 1960), GIMM and PFORR (1964), and many other writers postulate that the Bunter Sandstone must not be considered as a potential rockburst formation. Its base lies approximately 200 m above the extracted potash beds in all mining districts with flat-lying Zechstein sequences. For this reason the Werra potash mining district was believed to be safe against rockbursts.

TABLE 2-I

Statistics on rockbursts in German potash mining (after GIMM and PFORR, 1961, with additions as indicated in footnotes).

Year	Mine	District	Mine depth (m)	Dimensions of "destroyed areas underground (m)	(km^2)
1901	Ludwig II	Stassfurt	700	400 x 140	0.056
1917[1]	Angersdorf	Halle	740	300 x 100	0.03
1940	Krügershall/ Teutschenthal	Halle	660	2000 x 300	0.6
1943[2]	Schierstedt/ East	Halle	400	800 x 400	0.32
1953	Wintershall/ Heringen	Werra	500	1200 x 1200[3]	0.7[4]
1955[2]	Schierstedt/ West	Halle	400	1000 x 600	0.6
1958	Merkers II/III 2 mining levels	Werra	630 700	Various areas	2.8 2.0
1959	Neustassfurt VI/VII	Stassfurt	720	n.a.	0.09[4]
1961	Merkers III	Werra	700	n.a.	0.2[5]
1975	Unterbreizbach (Sünna)	Werra	800	n.a.	n.a.

n.a. = not available •

1) = 1917 according to GIMM and PFORR (1961, p. 35), LÖFFLER (1962, p.79) 1916 according to GIMM (1968, HÖFER and KNOLL (1971, MENZEL (1972), DREYER (1974a)

2) = Event dealt with in Chapter 3; no rockburst as defined in this text

3) = According to NEUWIRTH (1960)

4) = According to DREYER (1974a)

5) = According to PFORR and HOTTEWITZ (1967, p. 258). According to GIMM (1968, p. 257), the "destroyed" area was very small. According to DREYER (1974a), an area of 2 km^2 was "destroyed" (probably incorrect, see text)

Severe rockbursts during the early decades of potash mining at Stassfurt are not included in the much publicized German rockburst statistics. Some details are discussed in 2.2.1.

In contrast to previous practice, German writers fail to provide details on rockbursts which occurred after 1958. This appears to indicate the need for more changes to the hypotheses of potash mine pillar failure according to KVAPIL (1958) which were promoted for sometime after the 1958 rockburst (SPACKELER et al., 1960: GIMM and PFORR, 1961, 1964); see 1.2.2.1 for recent changes which are acknowledged.

KVAPIL (1958) investigated "splintering" failure of a variety of rock samples with relatively high compressive strengths; the test conditions included sudden loading in excess of the compressive strength, and changes to loading conditions of samples preloaded close to their compressive strengths. Salt-rock samples were not investigated.

The test results may apply to elastic rocks. However, salt rocks in-situ react by plastic deformation (creep) to loading and to changes in loading conditions, including stress relief due to the excavation of any opening. It is re-emphasized that under normal mining conditions, stress relief creep occurs ahead of advancing mine openings. The testing conditions applied by KVAPIL (1958) must not be compared with the loading conditions of salt and potash mine pillars. There is only one exception: the sudden reloading of mine pillars due to tensile failure of bridging overburden formations, i.e., due to rockbursts.

2.2 CASE HISTORIES, HALLE/STASSFURT DISTRICT

2.2.1 Some statistics incorrect

In Table 2-I, the 1901 rockburst at the Ludwig II mine, Stassfurt, appears as the first rockburst in a German potash mine; this is incorrect.

According to LÖFFLER (1962), the Leopoldshall I/II mine suffered a severe rockburst in 1879 which caused the collapse of an area of 20 000 m^2. In 1881 an area of 200 000 m^2 of the same mine collapsed, resulting in a small crater at the surface. The collapses caused tremors like natural earthquakes. Some more such earthquakes occurred until 1885. In 1900, this mine was abandoned and left to flooding, see 3.2.3 for details.

GIMM (1968) published two different versions of the early potash mining history; apparently, the differences reflect opinions of the respective assistants who wrote the two different chapters of the textbook (PFORR and

MEYER). In view of the differences between two chapters of the same textbook and of more differences between other publications, literal translations of the respective descriptions appear indicated. This writer's comments, if any, are put in brackets.

With reference to Fig. 2-7 GIMM (l.c., p.357, cowriter PFORR) reports (literal translation): "100 years ago the first potash mine of the world began operating at Stassfurt; at that time, mining experience had already been accumulated in other mining operations, so it was indicated to take advantage of such existing experience in selecting the mining methods to be used in the first potash mines; in particular, mining methods used in rocksalt and in hardrock ore mines appeared feasible. The first mining method used in mining the thick, steeply dipping Stassfurt potash bed is shown in Fig. 2-7: room-and-pillar mining without backfilling the rooms at different levels. Approximately 30 - 40% of the potash was extracted (WESTPHAL, 1902). 6 m of potash was left between rooms at different levels; the rooms were 6 m wide and 6 m high, and the pillars had the same width".

"In another potash mine at Stassfurt (Leopoldshall I/II), the room height of 13 m was chosen; the other conditions were similar. In 1878, after 16 years of operation, the first serious rock-mechanical effects were observed, and water began seeping into the mine. In 1900 the mine was left to flooding".

"40 - 50 years after the start of potash mining in the Stassfurt area several mines were lost to flooding as groundwater penetrated into the mine workings; this fact was decisive in the postulate to prevent, if possible, any overburden deformation by means of adequate pillars and additional backfilling of the mined-out rooms".

"During the early decades of potash mining the hydrological danger apparently was seriously underestimated; as a matter of fact, even the kainite immediately underneath the gypsum caprock was extensively extracted. As a result German potash mining engineers became extremely concerned with the danger of water inflow into potash mines".

"For many decades the dominant opinion was...that only room-and-pillar mining with pillars which remain very stable....is feasible to prevent deformation and ruptures above and below mined-out areas through which water can penetrate into the mines. Some practitioners still hold this opinion."

GIMM (1968, p.461, cowriter MEYER), provides the following information

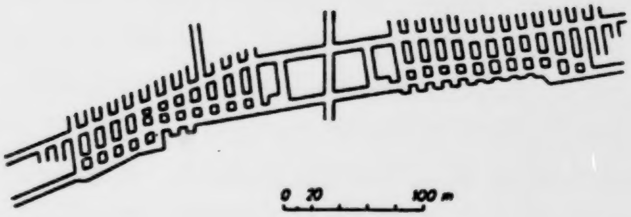


Fig. 2-7: Mine plan of the first potash mine, Stassfurt
(from GIMM, 1968; Bild 6/5)

on the mining methods used since 1861 in mining the kainite underneath the top of the Stassfurt anticline at the depth of only 230 m (literal translation): "The rooms (in the steeply dipping potash bed) were 10 - 12 m wide and up to 12.5 m high. The pillars were 5 m wide, and 5 m of ore were left between the rooms at the various levels (note the differences in the quotation from p.357). These dimensions were believed to provide sufficient support of the overburden, and the mined-out rooms were not backfilled. After 15 years of mining, observations (not identified!) indicated insufficient safety (apparently meaning insufficient stability). As the span of the mined-out area increased, the first room and pillar collapses took place in 1879, indicating heavy rock pressure... In 1882, the first large surface collapse occurred... In 1899 a large crater formed... Pumping ceased in April of 1900, and in June the water level in the mine shafts had already risen to 40 m below the surface... As the safety pillars against adjacent mines were only 28 - 130 m wide, these mines had also to be abandoned as the water penetrated through the safety pillars... The danger caused by mining without backfill and without strong pillars was recognized. Since 1884 the mined-out rooms were backfilled, the pillar width was increased to 6 m, and barrier pillars 32 m wide were left between panels of 10 rooms..."

DREYER (1974a, p.99) has the same story entirely different, but fails to indicate his sources; his report reads as follows (literal translation): "Around 1879 the first collapses resembling rockbursts took place. The extraction came too close to the water-bearing horizons in the kainite. Therefore it cannot be excluded that water inflows caused the damages to pillars and rooms, respectively, and the resulting events cannot be classified as rockbursts. The failure intensity of kainite resembles that of carnallite, so kainite must be considered as dangerous and able to cause rockbursts."

It appears that the quoted DREYER report was almost literally taken from GIMM (1968, p.233) whose text is also presented (literal translation): "In 1879 the first collapses in a potash mine resembling rockbursts occurred in the Leopoldshall I/II mine at Stassfurt according to the anniversary publication '100 years of salt mining at Stassfurt'. These events are peculiar because the extraction came too close to water-bearing horizons in the kainite; therefore it is impossible to clearly distinguish between causes and effects, i.e., between pillar or room failure and water inflows. It should be noted that kainite resembles carnallite in its failure intensity; it can be dangerous and cause rockbursts".

The preceding quotations clearly show DREYER's continuing belief in "splintering failure" according to KVAPIL (1958) as cause of the earth tremors registered on occasion of the collapses at Leopoldshall I/II. In contrast, the quotations from GIMM (1968) blame these collapses at insufficient pillar stability and resulting overburden deformations which in turn caused groundwater inflow into the mine.

DREYER's reasoning that possibly "water inflows caused the damages to pillars" and therefore "the resulting events cannot be classified as rockbursts", is definitely unacceptable since water inflows commenced after the first rockburst in 1879, i.e., the rockburst caused water inflows which could not be controlled for reasons outlined in more detail in 3.2.

Both GIMM's (1968) and DREYER's (1974a) publications are introduced as textbooks to be used at universities and as reference publications for practicioners; the quotations leave no doubt of the need for extremely careful exmaination of such textbooks. The continuing promotion of hypotheses which proved dangerous whenever applied in the design of salt and potash mines appears most regrettable; the following discussion of the rockburst statistics in German potash mining as promoted in the before-mentioned textbooks and numerous other publications intends to prove how dangerous the application of erroneous hypotheses can be.

2.2.2 Ludwig II mine, Stassfurt, 1901

Fig. 2-8 (shown by LÖFFLER, 1962, as Fig. 98 and attributed to JUNGHANS, 1952) caused some temporary confusion as it appeared in various publications. Again, in order to clarify this matter, literal translations of the respective parts of publications are preferred.

LÖFFLER (l.c., p. 185) reports: "In 1901 an accident resembling a rockburst took place at the Ludwig II potash mine shafts I/II; it claimed 17 lives. Floor heave occurred, and the rooms suddenly collapsed, including the salt left between rooms at various levels. The core underneath a stress arch subsided by 0.6 m. The fractures are still visible in the mined-out rooms in the Leine rocksalt (termed younger rocksalt in Fig. 2-8); it appears that these fractures were observed for the first time in 1908. E. KRZYWICKI (1950) reports that hardly any widening of the fractures occurred; the deformations ceased after the

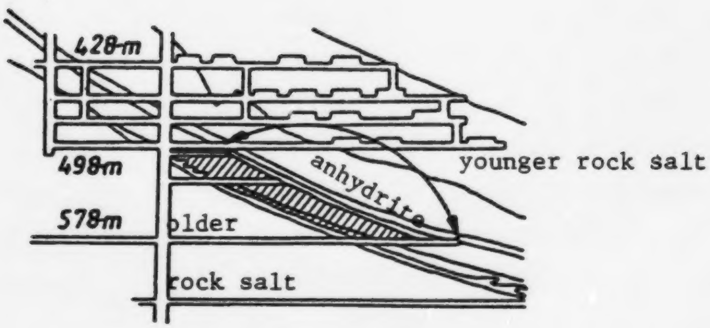


Fig. 2-8: Section through Ludwig II potash mine (after LOFFLER, 1962; Bild 98)

stresses had been released".

The same writer (l.c., p.192) provides the following additional information: "At Ludwig II, shafts I/II, several rockbursts occurred; all deeper levels collapsed in 1901".

These reports apparently are based on incorrect sources. However, Fig. 2-8 and the quoted explanations give the definite impression that the 1901 rockburst occurred above the 578-m level as indicated by the arrows at both ends of the so-called stress arch.

SPACKELER (1958, Figs. 9 and 10) shows Fig. 2-8 and a photograph as "particularly typical of the formation of a stress arch in a potash mine" and elaborates as follows (l.c., p. 166; literal translation): "Due to slow failure of the carnallite pillars in a mined-out potash panel, a roof arch formed in the overlying rocksalt panel; the stress arch became visible as the core of the arch separated from the overlying younger rocksalt. Fig. 10 (photograph, not included in this text) shows the smooth separation of the core approximately at the apex of the stress arch. As HÖFER already described the behavior of the salt pillars, it appears sufficient to provide the following additional information: over more than 30 years, the stress arch became more clearly visible; however, the surveys of the elevations show no more changes over the past 12 years, indicating that the stress arch has stabilized. The stress arch spans over more than 200 m across a mined-out panel with the length of approximately 500 m."

The writer (l.c., p. 167) theorizes: "The apex of the Ludwig-II stress arch reaches the maximum distance of 68 m from the roof of the underlying mined-out panel. If one assumes a symmetrical form of the stress-relieved zone underneath the potash panel, the ratio of the vertical to the horizontal axis of the ellipse calculates as approximately 150/200 or 3/4. A scientific explanation of these observations is still to be found".

These quotations also leave the impression that the 1901 rockburst occurred above the 578-m level, and led to some controversies in the published discussions of SPACKELER's presentation.

GIMM and PFORR (1961) clarified these matters by publishing Fig. 2-9 which represents a longitudinal section through the Ludwig II mine. The writers (l.c., p.32) comment as follows on the mining situation prior to the rockburst (literal translation): Fig. 2-9 shows "the strata dipping steeply near the top of the anticline; with increasing depths the dipping decreases, reaching only approximately 6 - 8 degrees at the maximum depth

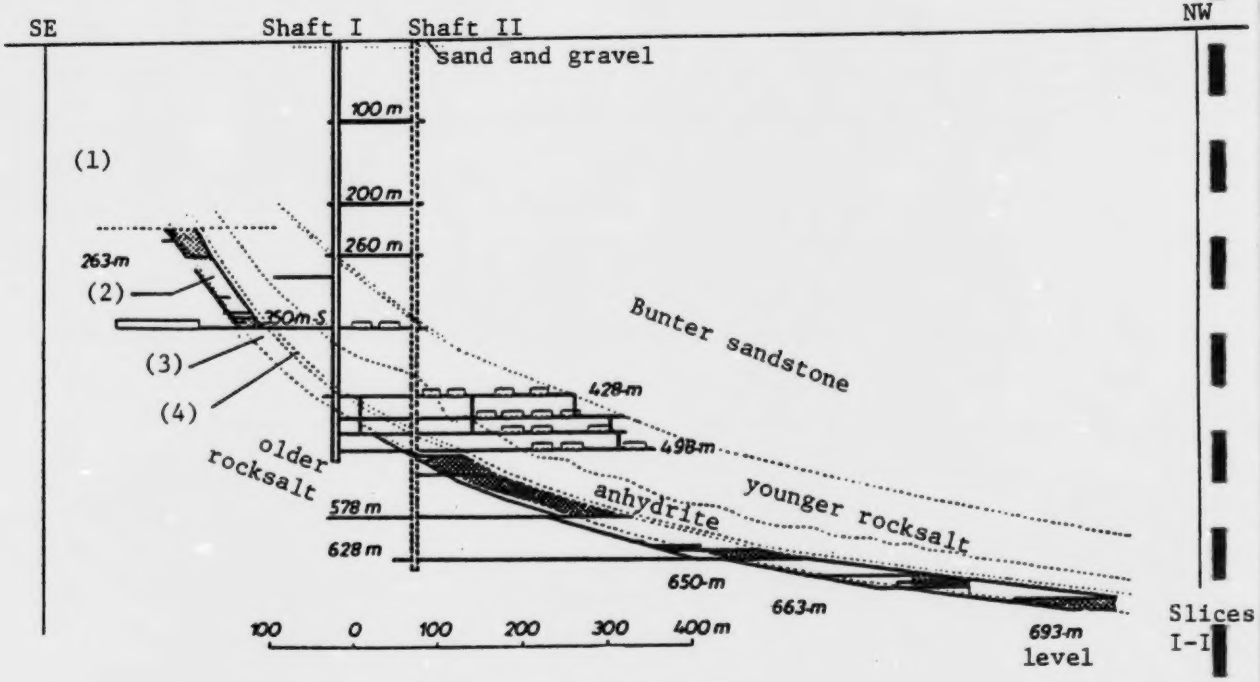


Fig. 2-9: Section through Ludwig II potash mine (after GIMM and PFORR, 1961: Bild 18)

(1) uppermost mining limit
(2) kainite
(3) carnallite
(4) saliferous clay

of 693 m. The rockburst occurred at the deepest level... The Bunter Sandstone reaches thicknesses over 500 m in the rockburst area... The pillars left in mined-out panels exhibited only little resistance against compression as the potash bed consists of strata of rocksalt, kieserite, and carnallite; in addition, some strata exhibit narrow folding".

It is emphasized that the stress arch shown in Fig. 2-8 is missing in Fig. 2-9.

In comparison with the disastrous collapses described in 2.2.1, the 1901 rockburst at Ludwig II appears as an event which would hardly deserve mention in textbooks. However, it claimed 17 lives and injured 47 more miners underground; this seems to be the reason why it is listed as the first rockburst in German potash mining, see Table 2-I.

The Ludwig I/II mine was squeezed in between other operating potash mines and surrounded by 200-m safety pillars. In the shaft area, the distance between the safety pillars was only approximately 300 m. Fig. 2-9 indicates that no shaft safety pillar was left. The length of the deepest panel above the 693-m level was only 400 m. The carnallitic potash bed was extracted in slices.

Fig. 2-9 explains why the span of the deepest panel increased with each slice extracted in the rooms: each slice had to be backfilled before the next slice approximately 5 m thick could be mined. The span of the first slice in the rockburst panel measured approximately 60 m; in the second slice the average span was 110 m, and the third slice measured 140 m. Fig. 2-9 indicates 4 extracted slices above the 693-m level; this appears to be an error which escaped correction, as the respective text mentions only 3 slices with spans as listed above.

GIMM and PFORR (1961, p.32) report room widths and heights of 15 m at the time of the rockburst. The two deepest slices were backfilled, so the pillars were embedded in backfill to the height of 10 m. The nominal pillar width was 10 m, contrasting to the previously quoted pillar widths of 5 to 6 m in the Stassfurt mines. The access entries to the panel were excavated along the safety pillar, leaving approximately 3 m of potash ore between entries and rooms and between the entries for the individual slices. The access entries to the two deepest slices were also backfilled at the time of the rockburst.

The panel affected by the rockburst measured 56 000 m^2 (140 x 400 m).

The tremors caused by the failure were felt at the surface. Heavy damage to the access entries to the mining panel caused the extraordinary death toll; apparently, the rockburst was triggered by blasting after the miners had left the panel. GIMM AND PFORR (1961, p.35) emphasize that the pillars in the rockburst panel were not affected; even decades later, there was hardly any change to the appearance of the open rooms. These remarks apparently are meant to stress the stability of the postulated stress arch across another mined-out panel, see Fig. 2-8; as shown previously, the Spackeler-Gimm school considered the arch-like separation void as proof of stable stress arches across mined-out room-and-pillar panels which are separated by barrier pillars.

Any interpretation of the mechanism of the 1901 rockburst must consider the following established facts: the span of the rockburst panel was only 140 m between much wider safety-barrier pillars; the general mine layout was a typical panel-and-pillar layout. Neither the 10-m pillars in the rockburst panel nor the much wider interpanel pillars were destroyed; the fatalities and injuries were caused by rock fall-spalling in access entries at the periphery of the rockburst panel.

These facts definitely rule out the explanation (HÖFER, 1958a) that the sudden separation of a rock segment from a stable stress arch represents the rockburst. Such a mechanism anticipates pillar failure which did not take place.

Both the effects of stress relief creep of the pillars in the rockburst panel and the elastic behavior of the overlying 40-m anhydrite plate must be taken into consideration. Elastic behavior of the anhydrite plate resulted in overburden load transfer to wide abutments around the panel. Due to stress relief creep, the panel pillars provided little support of the anhydrite. With the panel span increasing finally to 140 m, tensile stresses in the anhydrite plate increased until its tensile failure- the rockburst - occurred.

As a result of the tensile failure of the anhydrite plate, overburden load hitherto transferred to wide abutments was suddenly redistributed; additional load was instantaneously thrown onto much smaller abutments near the extracted panel. Such sudden loading is known to cause severe spalling off the "active" cross-section of openings in salt rocks, see Fig. 1-1; this applies particularly to carnallite in cases where shear fractures already exist because of the age of access entries.

After tensile failure of the anhydrite plate, arch-like separation voids may develop in the overlying rock salt formation as shown in Fig. I/5-30. As SPACKELER put it in his reply to WILKENING (1959) and BAAR (1959b): such arch-like separation voids in salt rocks must not be considered as stable arches as designed by architects and civil engineers who deal with elastic material.

2.2.3 Angersdorf/Halle potash mine, 1917

An apparent printing error which escaped correction (GIMM, 1968, Table 4/6) resulted in a strange chain-reaction: various writers, see Table 2-I, are listing 1916 as the year of this rockburst. The correct year is 1917 (GIMM and PFORR, 1961; LÖFFLER, 1962). This, of course, has no significance as to the rockburst mechanism; it merely indicates lines of rewriting without appropriate checking of reproduced data.

At the time of the rockburst, the dimensions of the affected panel were 100 x 300 m. Most writers who deal with this rockburst fail to give the room and pillar dimensions, but emphasize that the rooms were back-filled; possible damage to the carnallite pillars due to leaching is mentioned by most writers, but ruled out by GIMM and PFORR (1961, p. 39).

The room-and-pillar dimensions listed in Table 2-II show increasingly unfavorable w/h ratios of the pillars. The depth exceeding 700 m means thicknesses of approximately 500 m of the sandstone overburden. Needless to say that the sandstone formation supported itself over the small span of only 100 m of the rockburst panel. This excludes any reloading of the stress-relieved panel pillars by overburden subsidence. Most writers report roof settlements of 10 - 20 cm due to the rockburst, but also emphasize that the roof was found undamaged when the affected area was made accessible. The reported settlement may just indicate roof bed separation rather than settlement of the overburden. Surface settlements are not reported; however, tremors were felt at the surface.

GIMM and PFORR (1961, p. 36) and DREYER (1974a, p. 102) emphasize that the access entries were almost completely closed by rock slabs separated from the walls. These writers also stress that such spalling began prior to the rockburst; several days before the rockburst the spalling activity increased and mining was discontinued. Nobody was underground at the time of the rockburst.

The striking similarities with the Ludwig II rockburst in 1901 cannot be overlooked: mined-out panel suffered little, if any damage; no roof falls were observed; however, heavy spalling off the walls occurred in the access entries to the panel. These similarities indicate a similar mechanism, i.e., tensile failure of the Main Anhydrite.

TABLE 2-II

Angersdorf/Halle potash mine

A. Room and pillar dimensions (from HÖFER and KNOLL, 1971, p. 71; to comply with the numbering on the cited page, the second part of Table II of this publication should have been numbered Table III as in the publication by MENZEL, 1972)

Mining period	Depth (m)	Room width (m)	Pillar width (m)	Pillar height (m)	Ratio w (width) room/pillar	Ratio h (height) pillars	This writer's remark
1910-1912	700	20	15	9	1.33	1.66	Note the reduction of room and pillar widths while heights were not changed
1913	740	15	10	9	1.5	1.11	
1914-1915	740	12	8	9	1.5	0.9	

B. Calculated potential of pillar failure (II from HÖFER and KNOLL, l.c.; I from MENZEL, l.c., p. 352)

Mining period	Theoretical* pillar load (kp/cm^2)	Boundary pillar stress** (ultimate pillar strength) (kp/cm^2)		Potential of pillar failure		Safety factor
II	II and I	II	I	II	I	I
1910-1912	397	551	831	x	x	2.1
1913	425	275	606	xx	x	1.4
1914-1915	425	243	456	xx	x	1.1

x = potential of pillar failure according to MOHR criteria (elastic behavior anticipated) in the case of excessive loading

xx = "endangered by creep fracture" in contrast to "rigid" (x)

* = questionable, ** = extremely questionable, see text; stress relief creep upon excavation is completely ignored

2.2.4 Krügershall/Teutschenthal mine, 1940.

2.2.4.1 Erroneous assumptions resulted in heavy death toll

This rockburst claimed 42 lives and triggered extensive investigations into its causes. Exploration since 1947 revealed that most of the 42 miners survived the actual rockburst; they were trapped in the mine. Most mine workings suffered little damage, exactly as in the two previous case histories. However, the access entries between the main shaft and the mine workings suffered severe damage from spalling and floor heave and were virtually closed.

It was erroneously assumed that the whole mine had collapsed; no serious attempts were made to rescue the trapped miners.

GIMM and PFORR (1961, pp. 21 and 24), GIMM (1968, pp. 236-237), and DREYER (1974a, p. 105) are grossly incorrect in reporting that the whole mined-out area collapsed because of pillar failure.

GIMM and PFORR (1961, p. 40) speculate that the carnallite pillars were destroyed by splintering failure according to KVAPIL (1958).

However, the writers (l.c., p. 22) contradict themselves, reporting that access to the allegedly collapsed mine workings was established in 1947. The roof of mine openings was found in good shape; slabs had separated from the pillars, but not necessarily due to the rockburst. The trapped miners left messages written on the walls.

LÖFFLER (1962, p. 79) stresses the same point; investigations from 1947 to 1950 showed some spalling off the walls of some openings, and some floor heave. Roof falls were not detected.

In view of misleading publications by writers who advocate pillar failure as the cause of the rockburst, a detailed description of the mining practices at the Krügershall mine appears indicated.

2.2.4.2 Geology and mine development

All writers agree on the general dip of 6-7° of the carnallitic Stassfurt potash bed and the overlying formations.

LÖFFLER (1962) shows a typical section of the carnallitic potash bed mined at the Krügershall mine, see Fig. 2-10. Approximately 10 m of the Stassfurt potash bed were left as roof and floor of the rooms. The

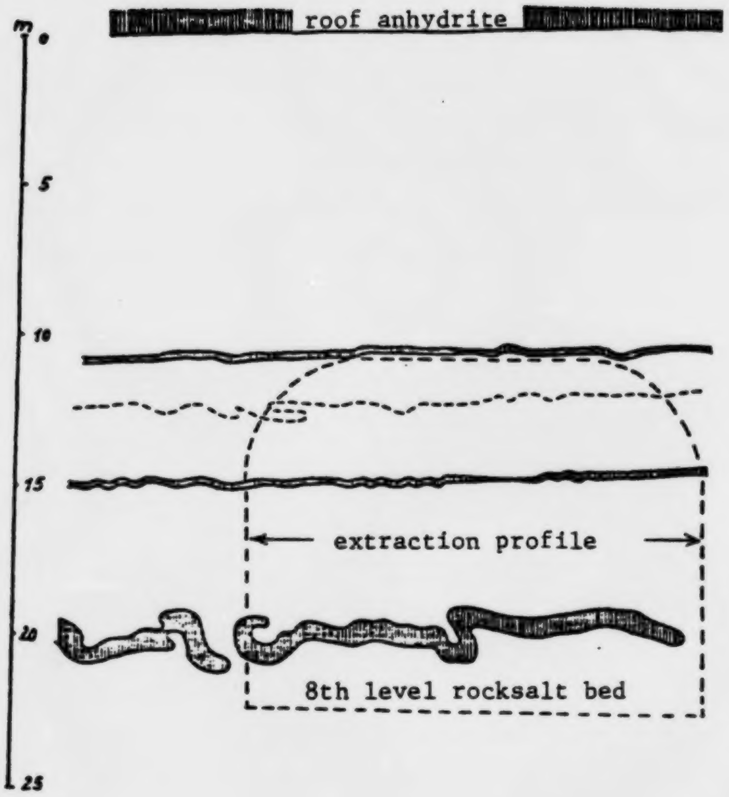


Fig. 2-10: Schematic stratigraphic section at Krügershall potash mine (after LÖFFLER, 1962; Bild 37).

roof section was given a favorable rounded form which accounts for the fact that no roof falls occurred. The roof section comes close to the "ideal" section shown in Fig.I/4-3. The floor section was not rounded; this explains why spalling off the pillars was a common feature prior to the rockburst.

Table 2-III shows the dimensions of rooms and pillars in various mined-out areas indicated on Figs. 2-11 and 2-12.

In addition to the rooms in the Stassfurt potash bed, 14 huge rooms were excavated 60-90 m underneath the potash bed in the underlying rocksalt sequence (area 4 of Fig. 2-12).

The mine was connected with a ventilation shaft at the distance of approximately 3 km.

LÖFFLER (1962) presents more geological details and analyses of the Stassfurt potash bed: the top 10 m of the potash bed were not mined because of high contents of clay and $CaCl_2$-minerals; the carnallite content increased upward from the underlying rocksalt sequence with the normal thickness of 500 m; however, there was no sharp and persistent boundary between the rocksalt and the potash bed.

DREYER (1974a, p. 106) believes that the pillars in mined-out areas were undercut by brines which seeped out of the backfill and dissolved $CaCl_2$-minerals. GIMM and PFORR (1961, p. 39) discount this possibility, emphasizing that there were very few, if any, $CaCl_2$-minerals present in the pillars, and upper parts of the pillars were not embedded in backfill, see Table 2-III.

2.2.4.3 Seismic data

The rockburst was registered by a seismograph located at the distance of 17 km. The seismogram, see Fig. 2-13, shows a light precursor 4 minutes prior to the main shock. 4 minutes after the main shock, another strong shock was registered. Six more aftershocks with the intensity of the percursor were recorded.

Seismic stations within the radius of approximately 700 km registered the rockburst as an earthquake.

Fig. 2-14 shows the surface perceptibilities according to the MERCALLI-SIEBERG scale, see Table 2-IV. The zone of the maximum intensity VIII covers approximately the mined-out area shown in Fig. 2-12. The

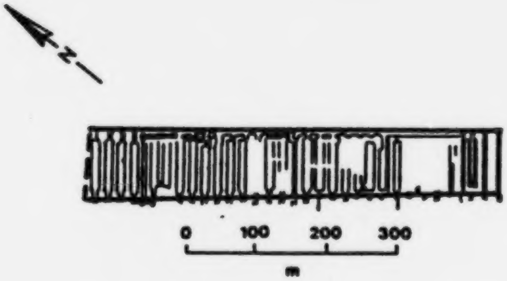


Fig. 2-11: Irregular mining patterns at Krügershall potash mine (after GIMM and PFORR, 1961; Bild 4), detail of mining area 3 southwest, see Fig. 2-12.

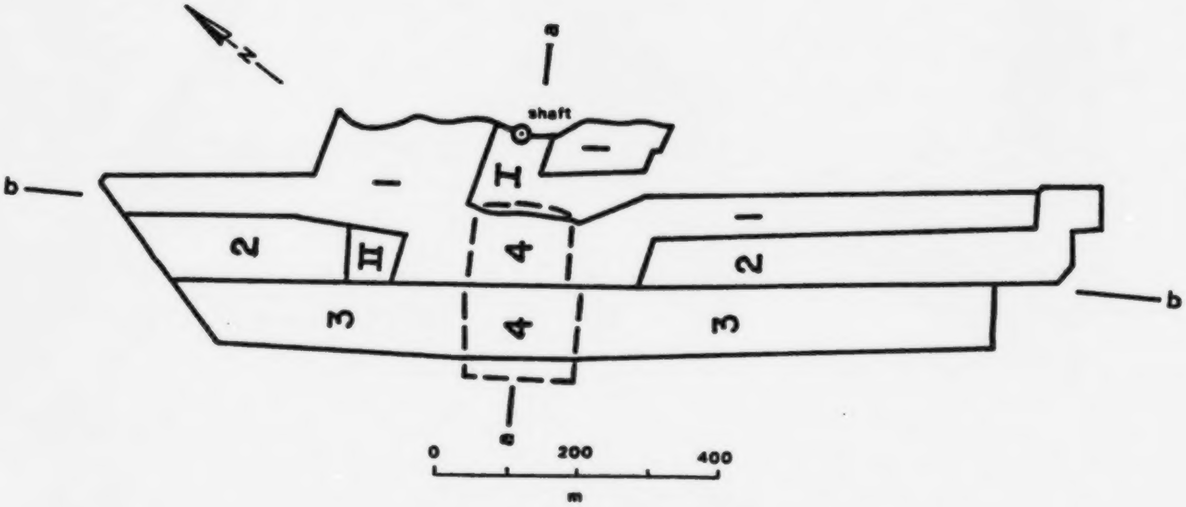


Fig. 2-12: Krügershall potash mine, mined out areas in 1940 (after GIMM and PFORR, 1961; Bild 4); showing safety pillars I and II, extraction areas 1, 2 and 3 (for detail of area 3 see Fig. 2-11), area 4 extensive rock salt extraction below potash bed. Subsidence profiles a-a and b-b, see Figs. 2-15 and 2-16.

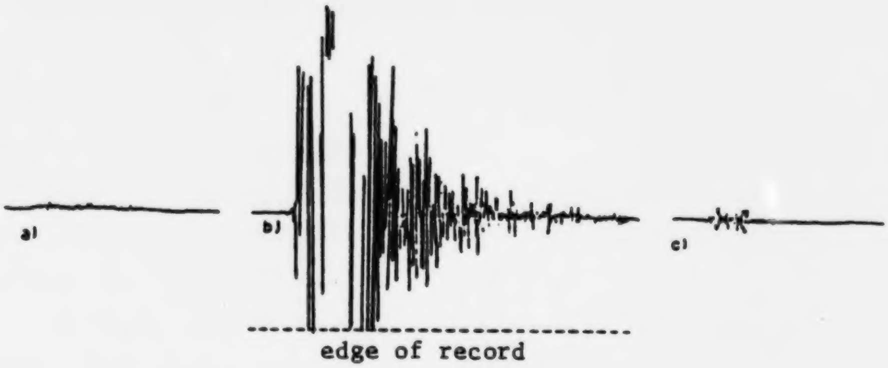


Fig. 2-13: Seismic record of the 1940 rockburst at Krügershall potash mine (after GIMM and PFORR, 1961; Bild 9); a) precursor, b) main event and c) first postcursor

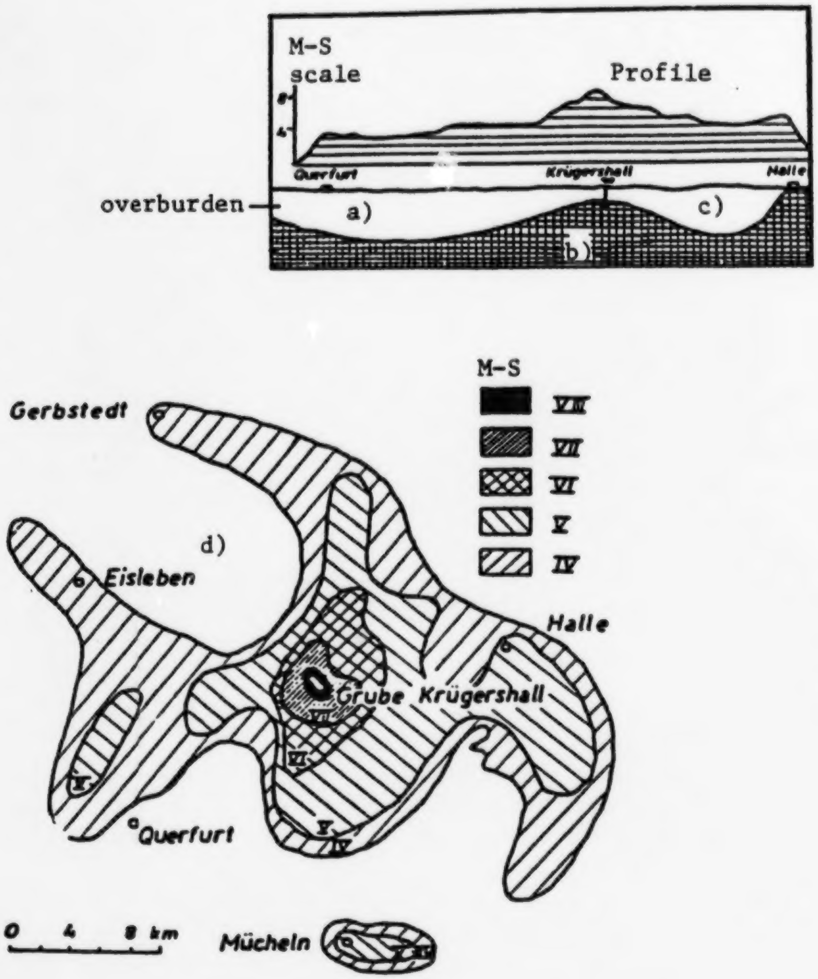


Fig. 2-14: Seismic intensity of 1940 rockburst at Krügershall (after GIMM and PFORR, 1961; Bild 10); in plan and section, using the Mercalli-Sieberg scale (M-S); a) Querfurt basin, b) Teutschenthal anticline, c) Possendorf basin, d) Mansfeld basin

TABLE 2-III

Krügershall mine; dimensions of rooms and pillars in metres (GIMM and PFORR, 1961)

Area	Room		Pillar		Ratios	
Fig. 2-12	length	width w	height h	width w	room/pillar w/w	pillar w/h
1	35	25	9	10	2.5	1.1
2	80	15	12	10	1.5	0.8
3	100	15	16	10	1.5	0.6
4	100	20	20	20	1.0	1.0

Mined-out rooms in the potash bed were backfilled to the roof until 1922; from 1922 to 1932, 2 m were left open; in 1933, 5 m were left open and 6 m were left open since 1934.
The mined-out rooms of the rocksalt panel, area 4, were not backfilled. Theoretical calculations of the potential of pillar failure (HÖFER and KNOLL, 1971; MENZEL, 1972) are not included in Table 2-III for reasons similar to those given regarding Table 2-II.

delineation of the zones of smaller intensities was dominated by the geological structure of the area; details can be found in LÖFFLER (1962).

2.2.4.4 Subsidence data

Surface subsidence measurements since 1909 are of particular significance in the interpretation of the mechanism of the rockburst.

Until 1935 the two subsidence profiles, Figs. 2-15 and 2-16, show very little surface subsidence. 1935 was the year of the last survey prior to the so called rockburst in 1940. The profile lines are indicated in Fig. 2-12.

The longitudinal profile, Fig. 2-15, shows the 1935 subsidence trough extending beyond the NNW boundary of the older mine workings. The maximum subsidence, about 30 mm above the boundary of the mined-out area and less than 50 mm above its centre clearly indicate the plate-like behavior of the overburden. This becomes apparent from a comparison with Figs. 7-3 through 7-7 measured in another mining district where

Table 2 IV

Mercalli-Sieberg Scale of seismic intensity (adapted from NEUMANN, 1964, p. 573-574)

Intensity	Surface Effects	acceleration cm/s^2
1	imperceptible - detectable only by instruments, microseismic shocks.	< 0.25
2	very slight - shocks felt only by very sensitive individuals.	0.25 - 0.50
3	slight - shocks felt by few people, only indoors.	0.50 - 1.0
4	moderate - shocks felt by many people indoors, but only a few outdoors.	1.0 - 2.5
5	fairly strong - shocks felt by many people even during full daytime activity.	2.5 - 5.0
6	strong - shocks felt by everyone with alarm, slight damage to some buildings.	5.0 - 10.0
7	very strong - small cracks in walls of many buildings, severe damage to some poorly constructed buildings.	10 - 25
8	destructive - trees sway extensively or break off; 25% of houses heavily damaged, some collapse; cracks appear in the ground.	25 - 50
9	very destructive - 50% of all stone buildings collapse, frame structures are moved from their formations.	50 - 100
10	devastating - massive damage to 75% of all buildings, most collapse; railway tracks are bent and pipelines sheared off; fissuring and buckling of roads; landslides.	100 - 250
11	disastrous - collapse of all stone buildings and bridges; some solid wood structures remain; dams break; wide fissures in the ground; many landslides. In historic times, intensity 11, on this scale has not been exceeded in larger cities.	250 - 500
12	cataclysmic - no man-made structure can withstand this force; extensive ground deformation, lakes empty, rivers are diverted, etc..	>500

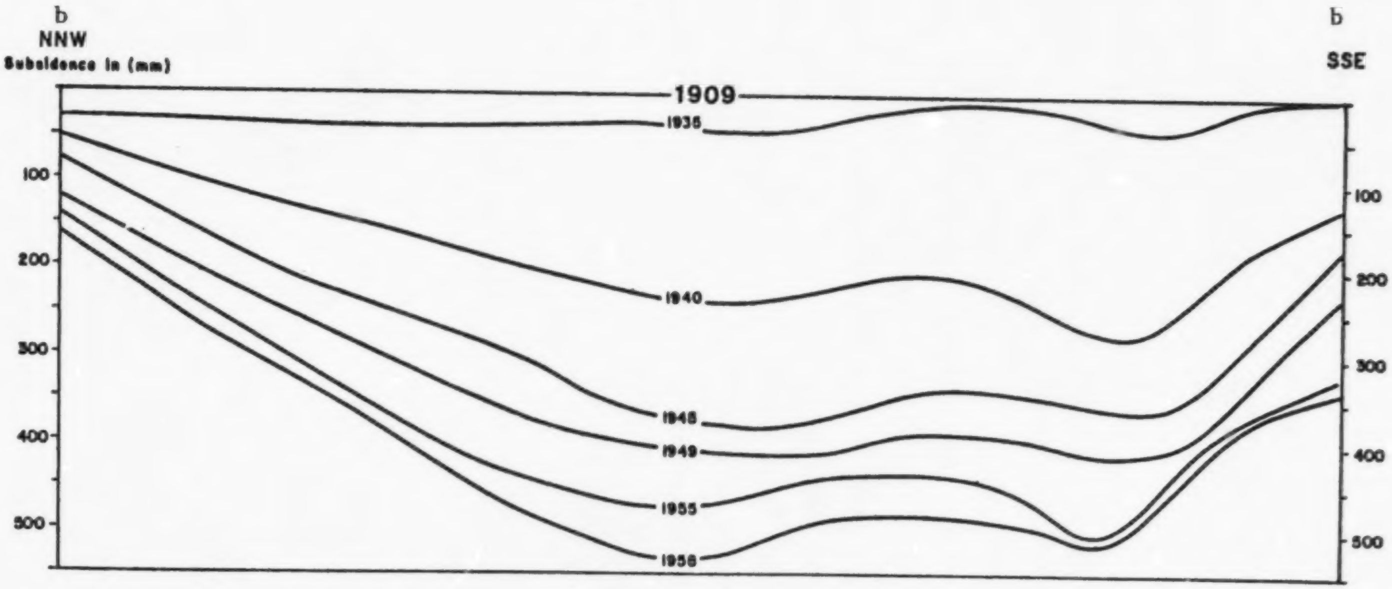


Fig. 2-15: Surface subsidence profile b-b at Krügershall 1909 to 1958 (after GIMM and PFORR, 1961; Bild 14) location shown on Fig. 2-12.

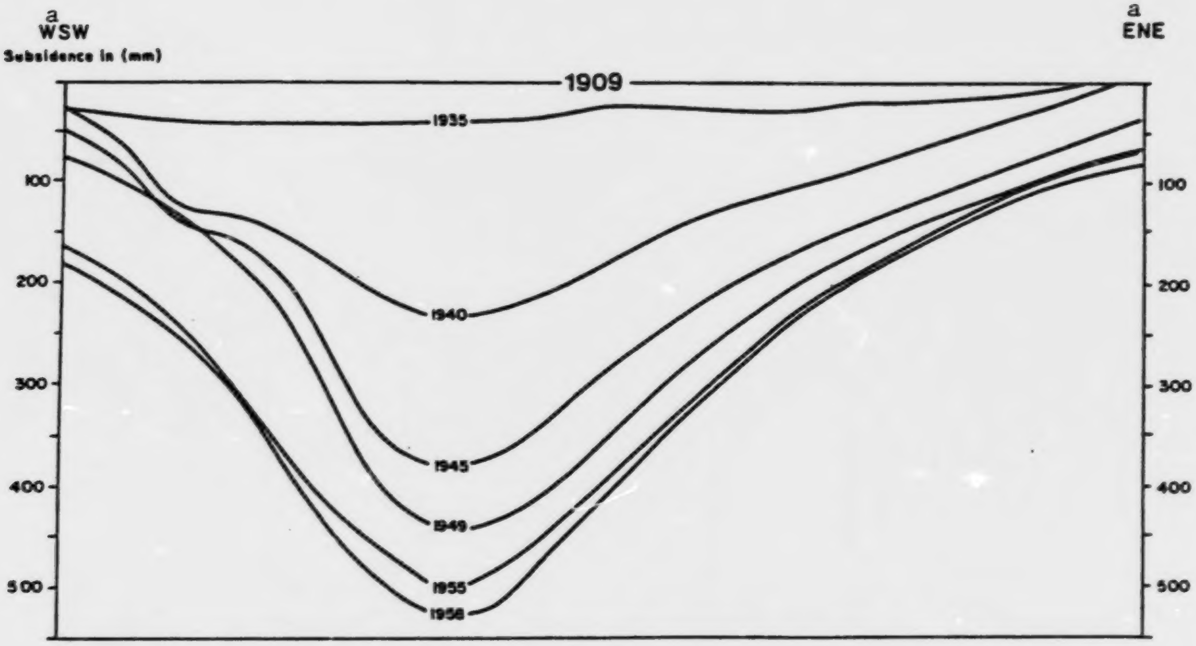


Fig. 2-16: Surface subsidence profile a-a at Krügershall, 1909 to 1958 (after GIMM and PFORR, 1961; Bild 13); location shown on Fig. 2-12.

the same sandstone formation is heavily fractured due to geological events in the past.

Fig. 2-15 indicates two separate troughs of maximum subsidence in 1935; the one in the center of the mined-out area is attributable to the rocksalt extraction underneath the potash bed. The separate trough near the SSE end of the profile reflects the increased pillar heights and the lack of effective backfill. The span of the mined-out area in this part of the mine was less than 300 m, so the plate-like behavior of the sandstone formation with thicknesses over 300 m cannot be considered unusual.

Fig. 2-16 also shows the effects of the rocksalt extraction; the surface subsidences extend far beyond the western boundary of the mined-out area. This phenomenon is not present at the opposite end of the subsidence trough, indicating the effects of the shaft safety pillar and of other large pillars left in this part of the mine.

In order to recognize the significance of the two 1935 surface subsidence profiles with maximum subsidences of less than 50 mm since 1909, the effects of stress relief creep in the potash panels and in the underlying rocksalt panel must be considered. Measurement data are not available; however, there can be no question as to the overlapping of stress relief creep zones in the pillars at both extraction levels. Backfill cannot reverse the effects of stress relief creep; effective overburden subsidence to reload the pillars did not occur until 1940 as demonstrated by the subsidence profiles.

The plate-like behavior of overburden formations prior to tensile failure is also apparent from Fig. 2-17. The rockburst occurred on May 24, 1940; the first survey after the rockburst was made in September 1940. Fig. 2-18 shows the contours of the surface subsidence trough after the rockburst.

Figs. 2-15 and 2-16 demonstrate that the subsidence rates developed into virtually constant rates which indicate little, if any, change to the deformational behavior of the main overburden after the rockburst. Point 64, located near the intersection of the two profile lines above the center of the mined-out area, shows an average constant subsidence rate of approximately 10 mm/yr.

A comparison with Table 7-II shows subsidence rates of this order of magnitude as normal for mined-out areas with spans smaller than the depths below surface.

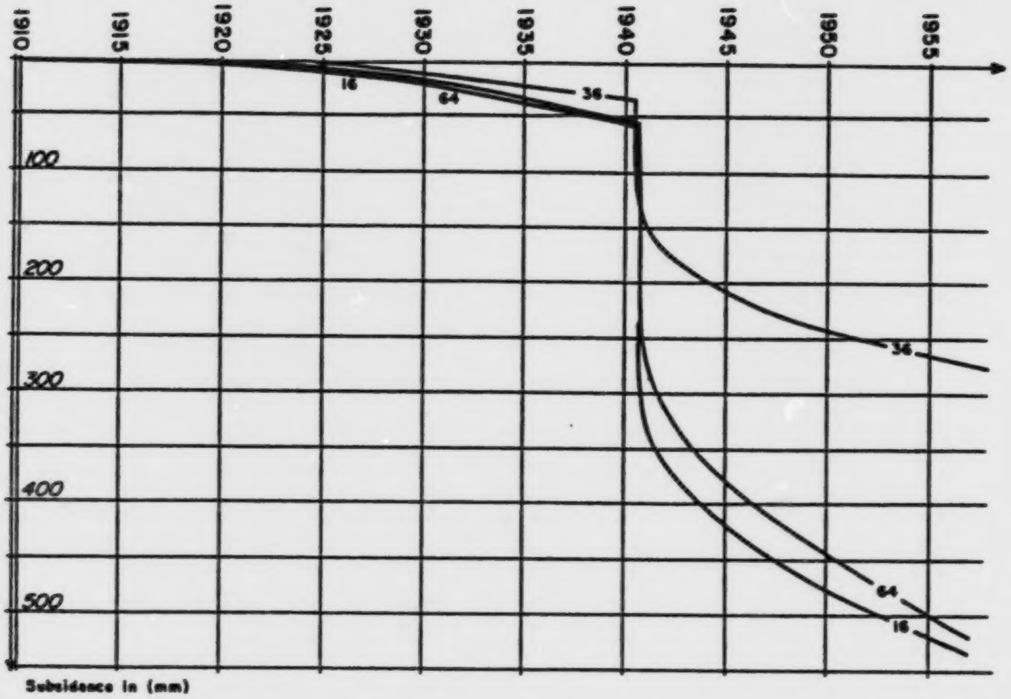


Fig. 2-17: Surface subsidence measured on typical points at Krügershall potash mine (after GIMM and PFORR, 1961; Bild 17)

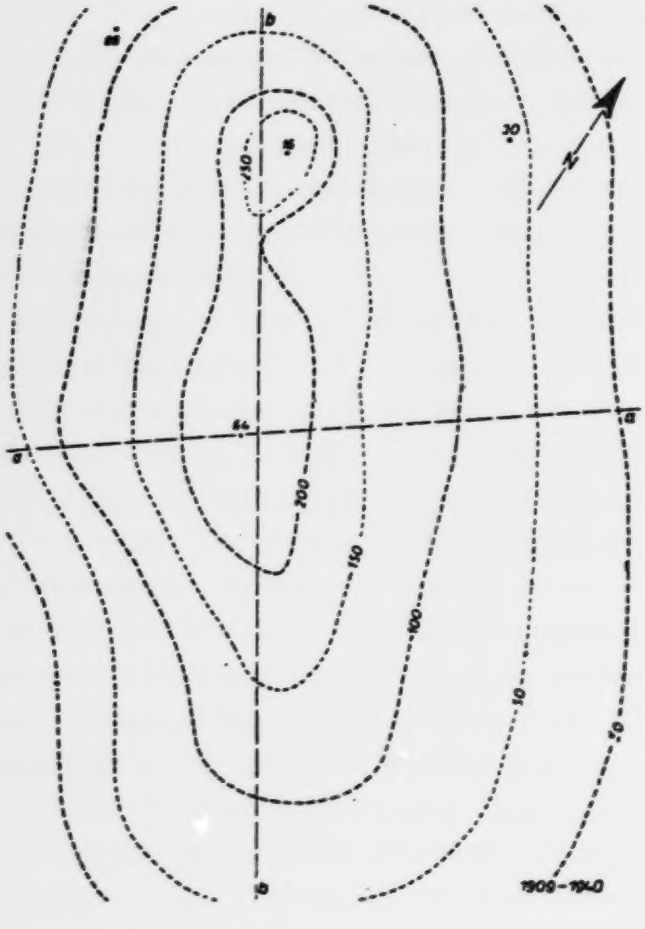


Fig. 2-18: Surface subsidence plan 1909 to 1940 at Krügershall potash mine, measurements approximately 3 months after the rockburst (after GIMM and PFORR, 1961; Bild 15).

2.2.4.5 Additional information

The following additional information appears relevant:

(1) During several weeks prior to the rockburst, peculiar observations were made in area 3 of Fig. 2-12 where extraction mining was in progress. The span of the mined-out area was approximately 200 m. Plate-like behavior of the sandstone formation apparently transferred load from the mined-out area to wide abutments.

One of the abutments was extracted in a rather irregular pattern; several remnant pillars were created; mining was in progress in such remnant pillars in the abutment load zone.

(2) Rapid stress relief creep caused unusual deformations, including slab separation at the faces, spalling off the pillars, and buckling failure of the roof due to lateral creep. The roof had to be supported to prevent caving prior to backfilling.

(3) During the last few weeks prior to the rockburst, mining crews were scared by the noises caused by rapid relief deformations; some refused to continue working in this area. The pillars were 10 m wide, but 16 m high; these pillars could not provide any effective overburden support.

(4) Similar observations were made in development entries, indicating the considerable width of the abutment around the mined-out area.

Most writers consider the described effects of rapid stress relief creep as indicative of pillar failure under excessive loads.

DREYER (1974a, p. 106) believes that sudden pillar failure caused the precursor to the main shock, see Fig. 2-13. The main shock is believed to have destroyed the pillars throughout the mine. The facts established since 1947 when the allegedly collapsed mine workings were investigated cannot be reconciled with such hypotheses.

2.2.4.6 Effects of safety pillars

The following effects of two so-called safety pillars, numbered I and II in Fig. 2-12, also confirm plate-like behavior of elastic overburden formations prior to the rockburst in 1940.

(1) Safety pillar I, with the minimum width of 100 m, separated the mine shaft and a small panel from the rest of the mine workings. The small panel, with dimensions of approximately 80 x 200 m, and the immediate shaft area were not significantly affected by the rockburst. Apparently, the safety pillar acted as abutment onto which additional

load was thrown due to the rockburst.

(2) Safety pillar II with the approximate dimensions of 110 x 130 m was left for the protection of 4 ammunition storage rooms in its center. This safety pillar limited the span of the mined-out area I of Fig. 2-12 to less than 200 m, and the span of the mined-out area 3 to the room length of 100 m.

The openings in safety pillar II suffered heavy damage from the rockburst; the destructions resembled those observed in access entries from the mine shaft to the mined-out area. Instructive results of investigations were published by PAWLIK (1943) and discussed by BAAR (1953c), GIMM and PFORR (1961), and GIMM (1968). BAAR (1953c, with discussions by SPACKELER, LEVI, JUNGHANS, BUCHHEIM) interpreted the mechanism of the rockburst as shown in Fig. 2-19.

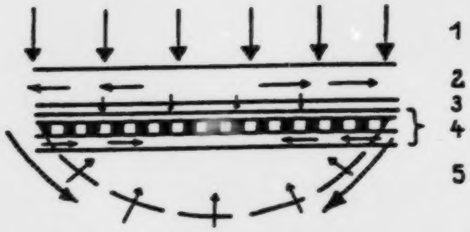
Fig. 2-19A shows plate-like behavior of the elastic formations, including the so-called Main Anhydrite, prior to the rockburst. The main overburden load was supported by wide abutments. Stress relief creep made the small pillars ineffective in overburden support. In old mined-out areas with rooms backfilled to the roof, the effects of stress relief creep were compensated to some extent by creep deformation of the underlying rocksalt as shown in Fig. I/5-22.

Fig. 2-19B is based on the assumption that excessive bending of the anhydrite plate resulted in tensile failure, leaving the main overburden without support above mined-out areas. Additional load was suddenly thrown onto the abutments near the extracted areas, and onto the safety pillars. It was transmitted by the underlying rocksalt as indicated; the small pillars were reloaded from the floor.

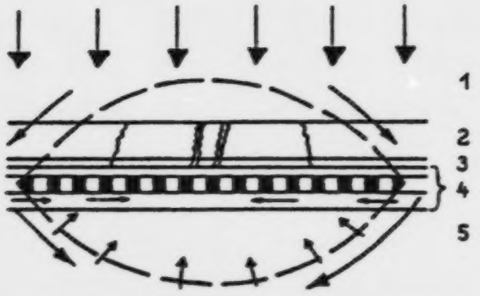
Salt rocks are known for their elastic reaction to sudden loading; however, creep deformations as indicated in Fig. 2-19 soon restore quasi-hydrostatic local stress conditions. Sudden load redistribution may result in temporary arching; in salt rocks, creep deformations as indicated soon remove any stress concentration.

The proposed rockburst mechanism was supported by SPACKELER and BUCHHEIM who emphasized that laboratory loads are usually applied too fast and result in brittle failure, in contrast to the in-situ loading conditions of mine pillars.

Since Fig. 2-19 was published, additional information became



A) Situation before rockburst. Top arrows indicate overburden load on 2 (Main Anhydrite). Arrows in 2 indicate tensional forces as pillars deform by stress relief creep. Overburden load, transferred to large abutments, causes creep in 4 and 5 as indicated by small arrows.



B) Situation after rockburst (tensile failure of 2 as indicated). Overburden load, transferred to smaller abutments as indicated by arrows, causes creep as indicated by small arrows.

Fig. 2-19: Interpretation of rockburst mechanism, Krügershall 1940 (from BAAR, 1953c; Bild 11)

1 - younger rock salt
2 - anhydrite
3 - saliferous clay
4 - stassfurt potash bed
5 - older rocksalt

available; it appears justified to further specify the rockburst mechanism as follows: the precursor, picked up 4 minutes prior to the main shock, may reflect the tensile failure of the anhydrite plate as indicated in Fig. 2-19. The failure process was initiated in the active mining area, see Fig. 2-4.

The sudden removal of support in the abutment of the bridging sandstone formation caused additional tension in this formation. Fig. 2-16 indicates rather abrupt surface subsidence near the western end of the profile, suggesting slip of the sandstone formation along the western boundary of the mined-out area.

Considering the span of 200 - 300 m of the mined-out area and the thickness of up to 500 m of the sandstone formation, one must assume a pre-existing zone of weakness in the sandstone, possibly a fault approximately parallel to the western boundary of the mined-out area.

The subsequent surface subsidence was controlled by creep of salt out of zones of stress accumulations into existing mine openings.

In view of the numerous publications which attribute the rockburst to pillar failure, it is re-emphasized that pillar failure did not occur. The constant subsidence rates after the rockburst clearly indicate safe control of the overburden subsidence by creep into the mine openings, including creep of the mine pillars which were reloaded on occasion of the rockburst.

2.2.5 Neustassfurt VI/VII mine, 1959

According to publications, the rockburst occurred on December 30, 1959. This writer was unable to make sense of contradictory reports published by various writers. For this reason, the published data are just compiled, and some literal translations from published reports are presented.

The Neustassfurt VI/VII mine operates on the NE flank of the Stassfurt anticline. The general dip of the Zechstein strata is 75 - 80° (LÖFFLER, 1962, p. 165).

The two shafts were sunk in 1912/1913 to depths of 420 (410) and 475 (690) m, respectively (LÖFFLER, 1962). The writer is not sure of the correct depths because of differing data from various sources.

Apparently the No. VI shaft was later sunk to the final depth of

690 m. The latter depth is also listed as the depth to the top of the Zechstein 2 rocksalt sequence.

These data indicate a dip of nearly 90°, confirming another report of a dip of 70-90° in both the No. VI and No. VII shafts.

The mine produced carnallite until 1923, rocksalt until 1954, and both carnallite and rocksalt since 1954. It was used for military purposes during World War II.

LÖFFLER (1962, p. 156) emphasizes that the Neustassfurt VI/VII mine is the only mine in the Stassfurt area which is still producing potash. The Stassfurt potash bed is reported up to 55 m thick (l.c., p. 190); only 20-25 m are extracted. The average compositions of the extracted potash ore and the extracted rocksalt are listed in the reference publication.

The writer (l.c., p. 185) reports roof collapses which occurred at the end of December 1959. In contrast to his detailed reports on other rockbursts, the writer gives no details, indicating that roof collapses are not considered unusual.

GIMM and PFORR (1961, p. 10) report "the sudden failure of the pillars in an area in which extraction was in progress"; "subsequent deformations were observed particularly in the floor strata of the potash bed." The writers assume "sudden splintering failure of the carnallite pillars in spite of their considerable width of 14 m."

GIMM (1968, Table 4/6) reports an extracted area of 0.09 km^2 destroyed by splintering failure of bedded carnallite pillars. The depth of the extracted area is listed as 530-560 m (l.c., Table 6/3); 25-30 m of the true thickness of the 50-m Stassfurt potash bed were extracted without backfill; room widths are listed as 12 m, pillar widths as 14 m.

The same writer (l.c., p. 393) reports room lengths of approximately 160 m. In contrast to the above-quoted report of sudden splintering failure, the writer reports pillar failures which occurred "in 1959, and later!" The writer stresses particularly the fact that the huge openings (160 x 25 x 12 m) were not backfilled.

DREYER (1974a, p. 107) reports quite different data: the depth is given as 720 m; the rooms are reported backfilled. The writer apparently disagrees with the hypotheses of splintering failure of carnallite pillars; "the rockburst caused some damage to the pillars, while the roof strata suffered no damage; it is not known for a fact if floor heave occurred."

This writer considers the data and descriptions given by LÖFFLER (1962) reliable as they are not biased by preconceived hypotheses.

Any assessment of the rock-mechanical situation must pay attention to the near-vertical dip of the strata affected by the excavation of the huge openings in carnallite. The dip lessens the effects of the deadweight of the sandstone formation at the flank of the anticlinal structure.

However, stress relief creep of salt rocks into huge excavations is not effected; the situation resembles that of solution-mined storage caverns with similar dimensions, see 4.2.4 and I/5.5.3. Over the vertical span of at least 160 m, the 50-m anhydrite was affected by stress relief creep into the carnallite openings at one side, and possibly by stress relief creep into rocksalt openings at the other side.

The condition of the anhydrite is not known; according to LÖFFLER (1962), hardly any information on pre-existing fracture patterns is available. None of the writers who theorize on the events provide information on the geometrical configuration of the existing openings. For these reasons, any interpretation of the mechanism which caused the failures would be merely speculative.

It is emphasized, however, that the span of the Main Anhydrite (160 m) is very similar to its span in the case histories 2.2.2 (140 m) and 2.2.3 (100 m). This similarity leads this writer to the assumption of tensile failure of the anhydrite in response to stress relief creep; the failure process may have been affected by local fracture systems in the anhydrite. The lack of necessary factual information disallows any substantiation of the assumption.

2.3 WINTERSHALL-HERINGEN, WERRA DISTRICT, 1953

2.3.1 Potash mines of the Werra district

The Werra potash mining district is the most important potash producer in both East and West Germany. The international border between the two countries runs in general NS direction through the Werra basin. Some factual information on the geology and the mining leases is to be presented for future reference.

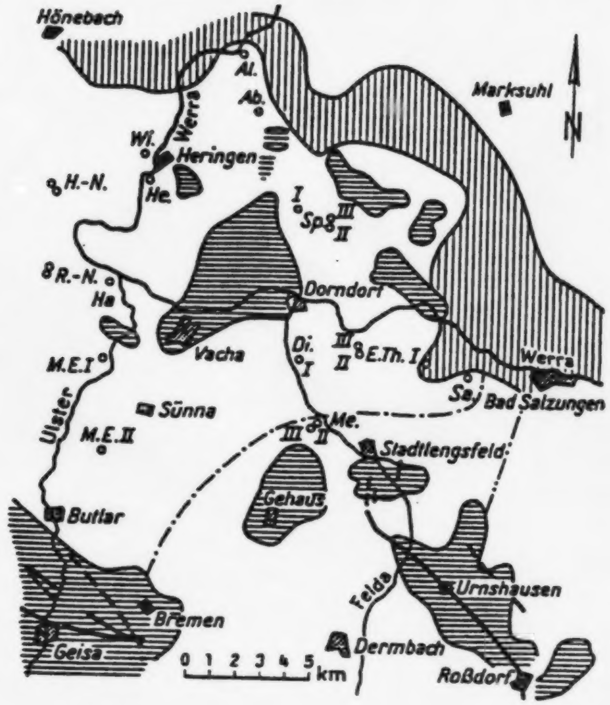
Fig. 2-20 (STOLLE in GIMM, 1968, Fig. 2/9) shows the locations of the mines relative to the most important geological features: the solutioned edge of the salt basin and several isolated areas where solutioning affected the salt deposit. The East German mines were organized into 3 operating units, Fig. 2-21, in 1972. Apparently, since then the organization was changed as MENZEL et al. (1980) refer to only one operating unit.

2.3.2 General information on the 1953 rockburst

The 1953 rockburst above the Wintershall-Heringen potash mine caused spectacular surface damage; fractures over 4 m wide, over 50 m deep, and over 400 m long formed instantly at the surface, delineating a block of the Bunter Sandstone formation which overlies the Zechstein evaporites. The sandstone block slipped down approximately 60 cm just southwest of the town of Widdershausen, see Fig. 2-22.

Damage to houses and other surface structures was considerable, as shown in publications (CORNELIUS, 1954; NEUWIRTH, 1960; GIMM and PFORR, 1961; GIMM, 1968).

According to hypotheses held at that time, see 2.1.3, rockbursts could not occur in the Werra potash mining district; some rather speculative interpretations of the 1953 earthquake were published. Some writers called for a tectonic earthquake, others assumed collapse due to natural salt solutioning at the top of the salt sequence. These publications, of course, were appreciated by the mining company which was not held responsible for damage caused by a natural event. Damage compensation



▥ solutioned edge of salt basin

▤ solutioning in salt deposit

• shaft

=·-= extent of the Hessen and Thüringen potash beds

— — zone of deformation

Fig. 2-20: General location maps of the Werra potash mining area (after GIMM, 1968; Bild 2/9)

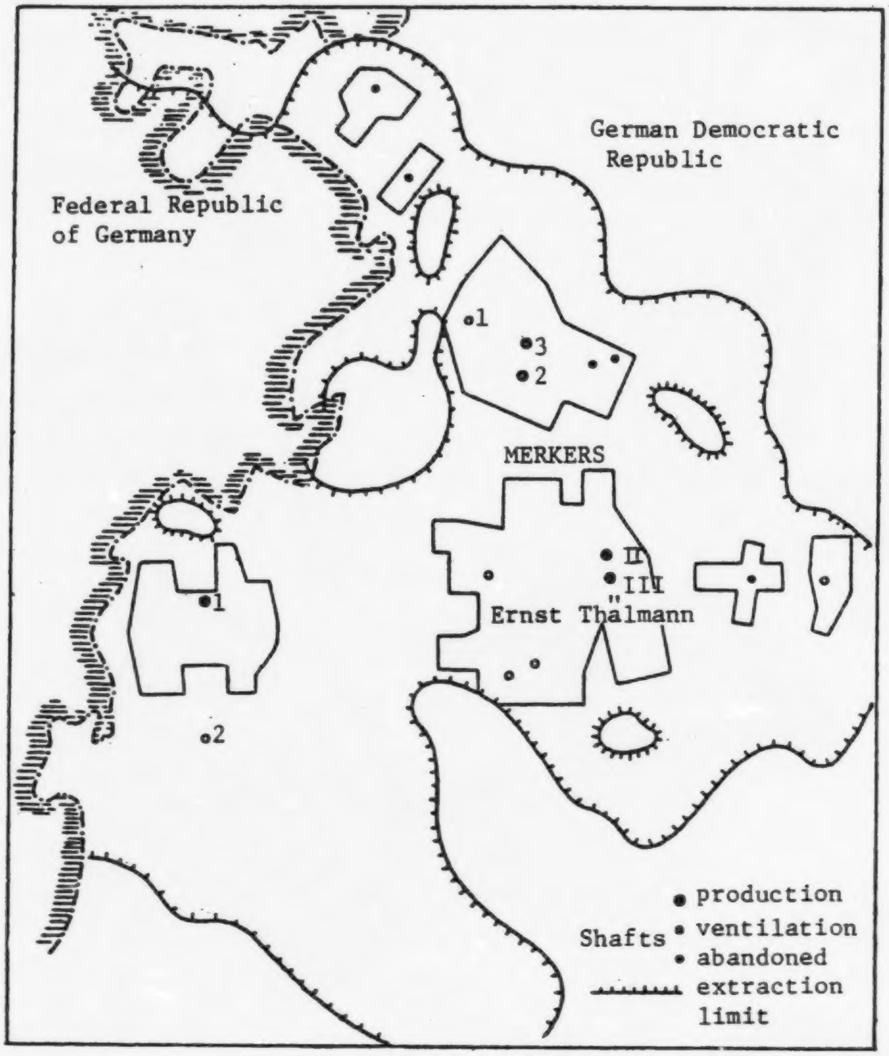


Fig. 2-21: Location map of the Werra potash mining area in GDR, lower level only, (after MENZEL, 1972; Bild 1).

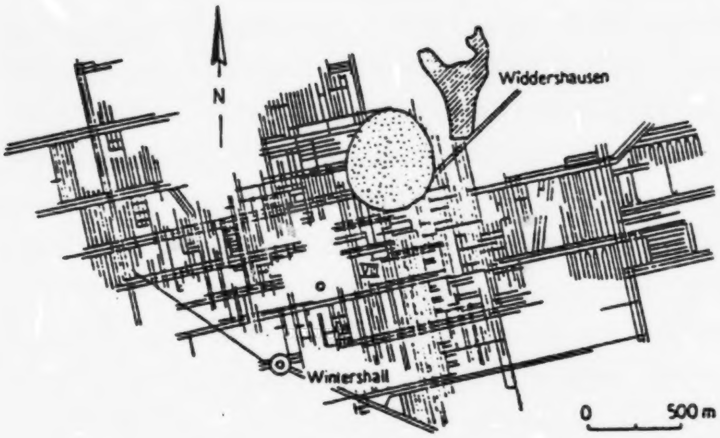


Fig. 2-22: Mine plan of the Wintershall-Heringen potash mine, upper level (after GIMM and PFORR, 1961; Bild 56) stippled circle indicates the 1953 rockburst area.

was left to the taxpayer.

These circumstances must be borne in mind in any assessment of publications which deal with the 1953 rockburst.

This writer became involved in controversies regarding the 1953 rockburst when summoned to defend his publications on the mechanics of rockbursts in German potash mines (BAAR, 1953c, 1954a) in front of an official committee which was dominated by representatives of the SPACKELER/GIMM school. The mechanism as outlined in 2.1 was presented but rejected; the controversies continued in publications.

However, the fact that the earthquake was caused by potash mining is no longer questioned (e.g., GIMM, 1968; DREYER, 1974a), and the most recent change in hypotheses, see 1.2.1.1 is welcomed.

As writers contradict each other frequently in factual matters, it appears indicated to present some relevant information on geological conditions. Fortunately, reliable information was established prior to the 1953 rockburst in publications which are not biased by attempts to promote certain hypotheses.

2.3.3 Geology and mine development

Fig. 2-22 shows the NE part of the Wintershall-Heringen mine in 1940. The area above which the 1953 rockburst occurred is indicated by a circle. In this area, local accumulations of carnallite were mined from 1933 to 1938. At that time pure carnallite was very much in demand for the production of metallic magnesium.

The thickness of the extracted carnallite varied locally. However, the various writers do not provide exact data or mine maps. Some of the published data may be cited for comparison.

NEUWIRTH (1960, p. 53), chief surveyor for the mining company, notes local thicknesses of up to 20 m.

GIMM and PFORR (1961, p. 88) have the thicknesses of the carnallite varying from 3 - 8 m, and to over 10 m in exceptional cases.

WEBER (1961) shows the distribution of carnallite on detailed mine maps, but fails to indicate its thicknesses.

DREYER (1974a, pp. 111-114) presents some sort of artist's conceptions of mine maps which differ entirely from those shown by other writers; the thicknesses of carnallite are given as up to 10 m.

Undoubtedly, the chief surveyor had the most reliable information on the thickness of extracted carnallite.

DREYER (1974a) also disregards or distorts other relevant facts; for example, the maximum length of fractures observed at the surface is given as 150 m; in fact, this is the depth of the fractures reported by GIMM and PFORR (1961, p. 91). The length was at least 400 m (CORNELIUS, 1954).

The latter writer and GIMM and PFORR (1961) emphasize that the surface fractures followed the directions of pre-existing fracture zones.

Detailed descriptions of the surface fractures (CORNELIUS, 1954) refer to a fracture zone "many kilometres long"; it is believed to have provided access for groundwater to the top of the Zechstein formations; salt solutioning is believed to have caused collapse of the sandstone formation.

2.3.4 Seismic data

CORNELIUS (1954) shows the surface perceptibilities of the 1953 rockburst, see Fig. 2-23.

The grade III-IV intensities coincide with the outcrops of the sandstone, similar to what Fig. 2-14 shows for the 1940 rockburst.

GIMM and PFORR (1961) show a similar map with apparent distortions; the W-E distances are shortened by 1/3 compared to the N-S distances.

CORNELIUS (1954) stresses the preferred E-W propagation of shock waves produced by sudden slippage on a "main" fault in the N-S direction, arguing that this observation characterizes the earthquake as originating in the sandstone formation. GIMM and PFORR (1961) call for sudden failure of overloaded carnallite pillars which would not have resulted in the propagation of shock waves in one preferred direction; the E-W distances on their map may have been shortened to arrive at a more uniform picture of the shock wave propagation.

2.3.5 Theoretical calculations

The salt sequence of the Werra basin is overlain by a cavernous dolomite formation with thicknesses of approximately 25 m. The porosity of approximately 10% and the effective thickness may be greater at some locations as the overlying and underlying shales are severely fractured. The dolomite is used for waste brine disposal, see 2.3.6.

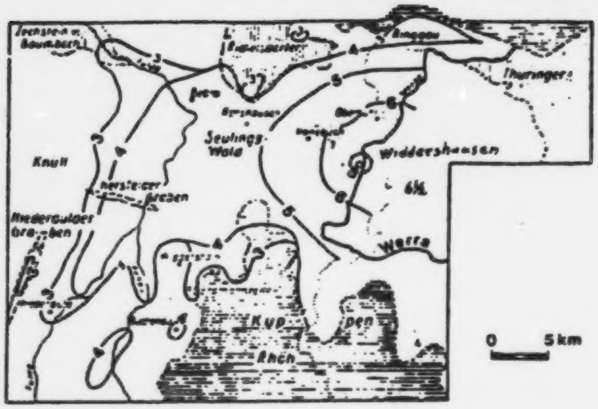


Fig. 2-23: Seismic intensity of the Feb.22, 1953 rockburst at Wintershall-Heringen potash mine (after CORNELIUS, 1954; p. 49). Lines of equal seismic intensity (3-8) are shown.

If and when stress relief creep of mine pillars initiates subsidence of the rocksalt sequence above mined-out areas, the brine pressure in the cavernous dolomite formation remains at approximately 30 kp/cm^2 (calculated from depth and gravity of the injected brines). The deadweight of the underlying evaporite strata above the mine workings is approximately the same. This means that pillars should provide approximately 60 kp/cm^2 of support even if the sandstone formation remains in its original position because of elastic behavior and insufficient spans. In such cases, the extraction of 2/3 of the carnallite bed results in average pillar loads of approximately 180 kp/cm^2. Corresponding subsidence of the roof salt sequence is to be expected.

Contradicting writers who believe in elastic behavior of the 100-m roof salt sequence above the potash mines of the Werra district, STORCK (1962) stresses the inevitable bending of the roof salt sequence in view of the plasticity of carnallite pillars. However, the writer ignores stress relief creep which most certainly had serious effects on carnallite pillars up to 20 m high.

STORCK (1962) leaves no doubt of the elastic behavior of the sandstone formation above the rockburst area. Assuming the tensile strength of 20 kp/cm^2 of the sandstone, the writer calculates the maximum span at tensile failure as 262 m; at this span, only 1.7 mm of subsidence of the bottom of the sandstone plate would occur.

The actual span of the mined-out area affected by the rockburst is given as approximately 840 m. The writer attributes the considerable discrepancy between the calculated and the actual span to support provided by pillars in the central rockburst area.

Theoretical calculations on the basis of assumptions are interesting academic exercises. However, they make little sense in cases where the elastic plate of sandstone is intersected by fractures in both the N-S and the E-W directions. This is known to be the case in the Wintershall-Heringen area; the tensile strength of the sandstone may be virtually zero normal to such fractures.

However, it is essential to know the extraction sequence in and around the rockburst area.

As emphasized repeatedly, the tension zones of separate subsidence troughs may overlap above non-extracted areas. If there are two pre-existing fracture systems intersecting each other, as is the case in the rockburst area, the possibility of zero tensile strength of the sandstone plate parallel to advancing extraction fronts is greatly increased.

2.3.6 Water movements in the overburden

FINKENWIRTH (1967) describes the disposal of waste brines through boreholes into the dolomite formation above the salt sequence.

Brine disposal operations in the Werra potash mining district began in 1925, and resulted in drastic changes to hydrogeological regimes. Natural salt solutioning processes near the outcrops of the dolomite formation are also affected: fresh water is supplied through fractures in the overlying sandstone; "in one system, fresh water descends and in the other saline water rises to the surface" (l.c., p. 124).

Solutioning resulted in what is called solution subsidence along the northern boundary of the Werra basin, and at some isolated locations indicated on maps. With reference to numerous other publications, the writer stresses the significance of Tertiary tectonic events; block faulting is considered characteristic, particularly in areas where salt underneath the sandstone formation was dissolved. Basalt dikes, following in general the N-S direction, are encountered at the surface, and in the potash mines where they usually run parallel to fractures filled with CO_2.

These and other effects of the Tertiary volcanism which affected the Werra basin are dealt with in some detail in I/2.4.3 and I/4.5.1.

Focussing on the Wintershall-Heringen area, FINKENWIRTH (1967) reports some observations related to the 1953 rockburst: several new springs appeared near Widdershausen, just east of the rockburst area; other springs became increasingly saline. In general, the front of the disposed brines advanced conspicuously to the north-east, as shown in Fig. 2-24. The writer attributes the spreading to increased disposal activities at both the East and the West German sides of the political border. In contrast, HÖFER et al. (1980) emphasize the termination of brine disposal in East Germany in 1968.

The fact that increased disposal activities may have contributed to the observed spreading is not questioned. However, the reported observations (new springs after the rockburst, increased salt contents in other springs) strongly suggest that huge amounts of disposed brines

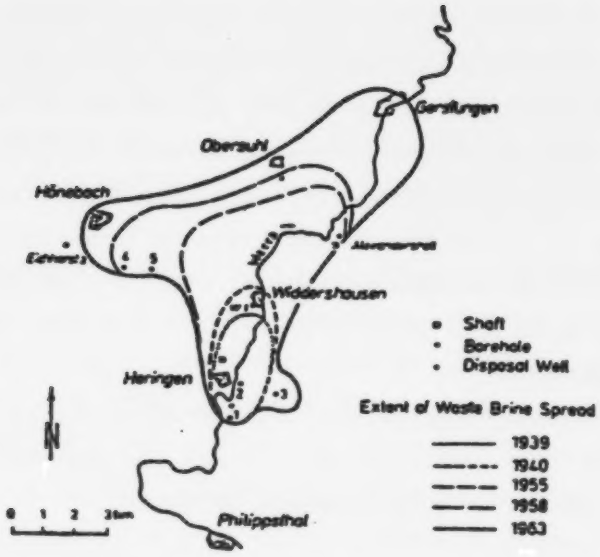


Fig. 2-24: Waste brine disposal spread 1939 to 1963 - Heringen area (after FINCKENWIRTH, 1967; Fig. 3)

were squeezed out of the dolomite formation from areas where the subsidence of the sandstone formation was no longer delayed due to the rockburst.

After the tensile failure of the sandstone formation which represents the 1953 rockburst, its deadweight had to be fully supported in the rockburst area. As outlined in 2.3.4, subsidence of the roof salt formation above mined-out areas with inadequate room and pillars must be assumed while the sandstone formation was behaving as a plate. The space created in this way was filled with brines under hydrostatic pressures of approximately 30 kp/cm^2 as long as the plate-like behavior of the sandstone formation prevented surface subsidence.

This obstacle to subsidence was suddenly eliminated by the rockburst. The pressure on the brines in the dolomite formation doubled and forced brines out of the dolomite formation, contributing to the conspicuous spreading of brines shown in Fig. 2-24. Continuing surface subsidence is to be expected.

At least some information on the development of the surface subsidences after the rockburst is required for a reasonable assessment of the genuine merits of this possible mechanism.

2.3.7 Surface subsidence

The company which owns and operates the Wintershall-Heringen potash mine refused to provide any subsidence data; this makes it necessary to continue piecing together essential information from publications.

Important information on the mine development and on surface subsidence after the 1953 rockburst is published by NEUWIRTH (1960). The writer is adamant in his attempts to show that the earthquake was a natural event. Apparently, he believes that there is nothing wrong with underdimensioned carnallite pillars up to 20 m high. To prove this point he refers to convergence measurements conducted since 1932; the locations of three convergence stations are shown inside the boundary of the rockburst area, either close to its boundary or next to large remnant pillars, respectively. At these three stations, the measurements were discontinued after the rockburst because of apparent bed separation.

The writer fails to present measurement data, but claims that the measured convergences were small over the entire measuring period of 25 years. This conclusion certainly cannot be valid for the central rockburst area with extremely high pillars; as emphasized in 2.3.5, these pillars had to support average loads of approximately 180 kp/cm^2. Under such conditions, considerable convergences are inevitable.

The writer places particular emphasis on one station with only 4-mm of convergence measured over 12 years; no details are presented, so no reasonable appraisal of the 4-mm convergence is possible. However, this station is mentioned here because of its location underneath a separate surface subsidence trough dealt with in great detail by the writer. Three photographs show the apparent horizontal compression in the N-S direction, contrasting to tension fractures 4 m wide which are shown in a number of photographs published by CORNELIUS (1954), and by GIMM and PFORR (1961).

According to NEUWIRTH (1960), 2.22 m of surface subsidence were measured in the centre of this separate subsidence trough from June, 1952, to December, 1954, Its axis coincides approximately with the southern periphery of the rockburst area, and extends to the SE towards an experimental mining area with 80% extraction, see I/5.2.5 for details.

The writer is linking the course of the axis of the surface subsidence trough to the course of a known fault zone in which local salt solutioning occurred at distant locations. Salt solutioning is also postulated to have caused the measured subsidences; the trough is believed to have developed towards the edges of the sandstone block which suffered 60 cm of instant subsidence after tensile failure in 1953, as evidenced by CORNELIUS (1954).

NEUWIRTH (1960) fails to mention the 4-m wide surface fractures near the 1953 rockburst area at least two different mechanisms were at work; one mechanism caused the instant settlement of a sandstone block; a second mechanism caused a separate, elongate subsidence trough with maximum depths of 2.22 m within 2 years!

It is definitely not possible to relate the development of the elongated subsidence trough to salt solutioning as speculated by NEUWIRTH (1960). For decades the area had been used for disposal of brines which prevented any salt solutioning at the top of the evaporites, see 2.3.6.

2.3.8 Extraction sequence led to rockburst

Sufficient information on the excavation sequence is available in publications. However, it is another tedious procedure to compile the relevant pieces of information from various publications.

Considering the large extent of mined-out areas in the Wintershall-Heringen mine, the reader should keep in mind that changes to mine development patterns require considerable preparation, such as development of haulage systems, ventilation systems, etc.; for this reason the extraction of any given area is usually terminated when the planned amount of ore has been taken out.

During the first decades of mining, carnallitic potash ore was not mined. As the lower potash bed is largely carnallitic, only the upper bed was extracted at the time of the rockburst. Extraction plans had to be changed several times because of unexpected geological conditions; the interested reader is referred to HARTWIG (1954), HOPPE (1958, 1960), and WEBER (1961).

The double-entry in the NE corner of Fig. 2-22, passing by the SE corner of the town of Widdershausen, was halted for such reasons in 1930; it was to meet with a development entry driven from an adjacent mine which ran into a basalt zone; the plan to connect the two mines was abandoned after several gas outbursts.

NEUWIRTH's (1960) maps show that the development entry was utilized to achieve effective ventilation for the area to be mined west and northwest of what became the rockburst area in 1953. No extraction mining was done underneath the town of Widdershausen. Apparently, surface subsidence and related damage to buildings was anticipated.

Fig. 2-22 shows the situation in 1940 when the extraction of pure carnallite in the rockburst area was terminated. A comparison with other published mine maps shows that indeed no further mining was done in the rockburst area after 1940. The maps show several barrier pillars in the rockburst area. The number of smaller pillars between such barrier pillars is changing, probably depending on the thickness of the extracted pure carnallite.

DREYER (1974a) shows different locations for most of the barrier pillars; his statement that every eighth pillar was a 40-m barrier pillar is definitely incorrect. The reader is also cautioned regarding other statements and figures published by DREYER (1974a): the writer reports room and pillar widths of 16 m and 12 m, respectively; elsewhere (l.c., p. 112), room widths varying from 17 to 20 m, and pillar widths of 10 m are reported. However (l.c., p. 144), the pillar shown in a figure is only 8 m wide.

Such apparent contradictions are insignificant in view of the heights of the pillars; regardless of the actual pillar widths, stress relief creep severely affects the supporting capacity of high carnallite pillars.

The effects of stress relief creep were particularly serious in areas which are easily identified on Fig. 2-22 : long rooms with standard lengths of approximately 250 m were excavated not only in one direction; cross-cuts with similar lengths left small rectangular or square pillars which could not provide any effective overburden support. The location of some barrier pillars appears to indicate resulting difficulties.

Some of the blank areas on mine maps published by WEBER (1961) are not barrier pillars, but areas which apparently collapsed on account of too many cross-cuts.

A comparison of Fig. 2-22 with the maps published by NEUWIRTH (1960) leaves no doubt of the cause of the 1953 rockburst. The reader is reminded of the termination of carnallite mining in the rockburst area in 1940.

During the years preceding the rockburst, the area west of the mined-out carnallite panels was extracted. The upper potash bed in the new area was also carnallitic (WEBER, 1961). In general, the extraction front advanced to the E from the location of the N-arrow in Fig. 2-22 . For reasons outlined above, the overburden subsidence above the old carnallite panels was still delayed by plate-like behavior of the sandstone formation; the sandstone plate was supported by abutments in virgin ground underneath the town of Widdershausen, and by large abutment pillars west of the carnallite panels.

As the extraction advanced eastward, the width of the latter abutment continuously decreased; horizontal tensile stresses began to develop in two opposite directions, overlapping above what was left of the remnant pillar between the two extraction areas.

At some point in time, which cannot be predetermined because of the unknown effective tensile strength of the sandstone plate in preexisting fracture zones, tensile failure of the sandstone formation took place; fortunately, the actual failure was triggered by blasting which is allowed only after the mines are evacuated.

One interesting observation is reported by GIMM and PFORR (1961, p. 91) and by DREYER (1974a, p. 113); apparently, the latter writer just rephrased the report of the former writers which reads: the pillars in the rockburst area suffered heavy damage; large pieces of salt (spalls) fell off the pillars. For several minutes, salt dust was blown out of the mine shaft.

DREYER (l.c.) continues as follows: own observations confirmed this report (attributed to SPACKELER, 1957). In the main collapse area, the remarkable roof subsidence resulted in compression of the pillars; some of the pillars in pure carnallite were completely destroyed. In such areas, fractures up to 20 cm wide were observed in the roof rocksalt; these fractures, exhibiting smooth surfaces, were extending several metres into the roof.

These descriptions indicate that the writer is not familiar with the geological conditions in areas where pure carnallite crystallized from ascending brines, see Fig. I/2-21. The reported fractures represent the passage ways of brines which ascended during the Tertiary volcanism along with CO_2. Such fractures are described in numerous publications, e.g., HOPPE (1958, 1960), and particularly HARTWIG (1954).

The latter writer (l.c., p. 19) refers specifically to such fracture zones with basaltic cores observed in the NE area of the Wintershall-Heringen mine, stressing the point that these zones were still awaiting exact mapping. Two such zones observed in the upper potash bed are described as extending over minimum lengths of 1.25 and 0.45 km, respectively. Another basaltic zone apparently prevented the development of the mine to the W, see Fig. 2-22, during the first decades of this century. Interested readers can find more details in WEBER (1961) who presents detailed maps.

The following point must be stressed here: apparently, some fracture systems filled with gas under high pressure were opened by the rockburst. Discharge of gases resulted in the reported blowing of salt dust out of the mine.

It goes without saying that pillar compression due to roof subsidence, as speculated by DREYER (1974a), cannot result in vertical fractures up to 20 cm wide in the roof of adjacent openings. Pillar compression results in horizontal compression of the immediate roof of openings; existing fractures are closed rather than widened. For further details regarding the effects of gas outbursts and gas exhalation after rockbursts, the reader is referred to 2.4.1.3.

There are serious doubts as to the credibility of DREYER's (1974a, p. 113) claim that he inspected the rockburst area and found the pillars completely destroyed. In the first place, no mine management and no mine safety authority in any country would permit a university teacher to enter a mined-out area in which all pillars collapsed for whatever reason.

Secondly, the writer (l.c., p. 113) claims that he took samples from pillars in the central rockburst area; his artist's conception of a mine map makes it impossible to identify exactly the locations. A comparison with exact maps indicates that samples were taken near the boundary of the rockburst area. Apparently, pillars from which samples can be taken cannot have been destroyed.

It is re-emphasized that NEUWIRTH (1960) makes no mention of any pillar failure in the rockburst area; he reports heavy spalling off the pillars, but also stresses that the 40-m barrier pillars ensured less underground subsidence than in mined-out areas with little or no carnallite.

2.4 MERKERS POTASH MINE, 1958

2.4.1 Misleading publications and laboratory experiments

2.4.1.1 Damage exaggerated

The participants in the Symposium on Oceanic Salts, June 16 - 22, 1958, Berlin (Freiberg. Forschungsh. A 123) were invited to inspect the Merkers potash mine. This writer took advantage of the rare opportunity. The guided tour followed an incline from the upper potash bed down into a mined-out room-and-pillar area in the carnallitic lower potash bed, see Fig. 2-25 (dotted line in the safety pillar against the adjacent Dietlas Mine). The same incline is shown on the map of the lower level, Fig. 2-26.

On July 8, 1958, less than 3 weeks after the visit, the area suffered severe damage from the largest rockburst, see 2.1.1 and Table 2-I.

It appears safe to assume that the group of international visitors was not guided into a mined-out area believed to be endangered by an impending rockburst. In other words, the 1958 rockburst came fully unexpected as did other rockbursts above German potash mines.

However, there were unmistakable indications of the rockburst potential in the inspected area: severe spalling off pillars, apparently due to original rectangular cross-sections of all openings; spalling and separation of roof and floor segments according to Fig. I/4.3 were particularly conscpicuous in older openings with limited widths, such as the access entries to the long rooms.

These observations were thoroughly discussed with attending Russian experts who agreed with this writer's interpretation of stress relief creep, see I/4.2. In contrast, East German theoreticians continued to postulate stress concentrations near the openings; these stress concentrations would secure stable pillar cores, and would prevent any overburden subsidence, particularly in areas of carnallite extraction.

With reference to the 1953 rockburst, the East German theoreticians were urged again to reconsider their hypotheses as extensive spalling in carnallite panels in combination with elastic behavior of overburden plates may indicate an imminent rockburst danger.

The 1958 rockburst indeed occurred only a few weeks later. However, erroneous hypotheses were again presented to an international audience (HÖFER, 1958b; BUCHHEIM, 1958; SPACKELER, 1958). WILKENING (1959)

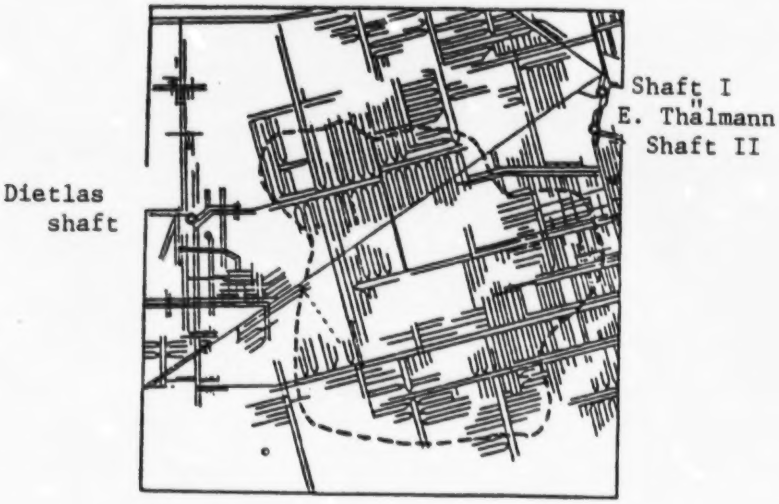


Fig. 2-25: Schematic mine plan - upper level - of the potash mine 'Ernst Thälmann' II/III, Merkers (after GIMM and PFORR, 1961; Bild 33); the dashed line indicates the alleged boundary of the July 1958 rockburst.

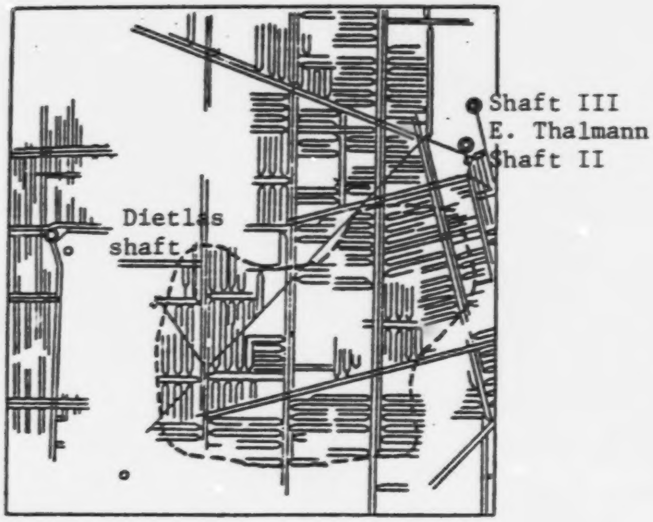


Fig. 2-26: Schematic mine plan, lower level, of the potash mine 'Ernst Thälmann' II/III, Merkers (after GIMM and PFORR, 1961; Bild 34b); the dashed line indicates the alleged boundary of the July 1958 rockburst.

and BAAR (1959b) considered it necessary to show these hypotheses dangerous. However, the East German theoreticians ignored the warnings and published their grossly exagerated reports on underground damage in the Merkers mine.

There are various reasons for the exaggeration of underground damage attributed to the 1958 rockburst. Compared to the spectacular surface damage caused by the 1953 rockburst, there was little to show at the surface above the Merkers potash mine. However, SPACKELER et al. (1960), GIMM and PFORR (1961), GIMM (1968), and particularly DREYER (1974a) claim that large underground areas were destroyed by the rockburst. The latter writer reports that he inspected the destroyed areas, but fails to explain how collapsed areas could possibly be inspected, even if "mainly and only" the pillars were destroyed.

GIMM and PFORR (1961) indicate the source of the exaggerated damage reports: the damage attributed to the rockburst was assessed by a group under the direction of the mine manager. According to production plans, the Merkers mine had to show the biggest output among all East German potash mines; the mine manager may just have been seeking an excuse for not producing the planned production.

The observations made only a few weeks prior to the rockburst are re-emphasized; a group of international visitors cannot be guided into mined-out areas which are several decades old; in such areas, spalling off the pillars reaches considerable proportions due to long-term creep deformations.

In the assessment of the damage attributed to the rockburst, spalling off pillars was used as the principal criterion in delineating zones with different degrees of alleged pillar failure. The resulting maps, published repeatedly by various writers, are meaningless, particularly regarding mined-out areas in the upper potash bed where sylvinite with thicknesses of 1.8 - 2.5 m had been extracted for many decades. Approximately 50% of the "destroyed" area were not extracted at all because the ore quality was considered inferior.

According to GIMM and PFORR (1961), carnallite with thicknesses up to several metres had been mined only in a few relatively small areas in the upper potash bed; the reasons are outlined in 2.3.2. The writers show these mined-out areas surrounded by large remnant pillars and/or sylvinite pillars with normal heights; these long pillars are 10 m wide, their w/h ratios are 4 or better. These pillars support the full deadweight of the overburden; superficial spalling is mainly attributable to blasting and/or gas outbursts. The reader is referred to Fig. I/5-14 which shows room convergences of only 100 mm measured over 25 years prior to the 1958 rockburst.

The meaningless maps, showing different degrees of pillar damage according to the assessment team, are not shown in this text. However, readers who consult the reference publications should notice that the southern boundary of the "destroyed" area is shown outside the mined-out area in the upper potash bed. At the western side of the mine, see Fig. 2-25, the rather arbitrary mapping is even more obvious: approximately one half of the total length of the boundary of the "destroyed" area is shown running across a large safety pillar against another mine. It goes without saying that nobody can inspect the interior of a 300-m safety pillar to determine the boundary of the damaged area.

According to the maps, the SW part of the mine workings in the lower potash bed suffered most severe damage from the rockburst; this area was inspected less than 3 weeks earlier, as emphasized above. At that time, the damage criteria were already clearly visible, and their significance was discussed in detail. The arbitrary damage assessment by mine employees led to rather questionable conclusions (SPACKELER et al., 1960, with discussions; GIMM and PFORR, 1961, with special appendix by KVAPIL and PFORR; GIMM, 1968; DREYER, 1974a) which need to be discussed in detail.

2.4.1.2 Comparison with longwall coal mining misleading

The writers referred to postulate considerable overburden load concentration on remnant pillars; however, the regular long pillars are also believed to support the full overburden load according to depth and extraction ratio. The latter postulate (HÖFER, 1958a,b; BUCHHEIM, 1958; other writers) appears acceptable regarding long sylvinite pillars with heights up to 2.5 m and widths of 10 m. It has never been questioned that such sylvinite pillars can support the full deadweight of the overburden of large mined-out areas.

If the regular pillars support the overburden, then it makes no sense to postulate overburden load concentration on remnant pillars and other abutments.

However, overburden load concentration on remnant pillars in the upper potash bed at Merkers is the basic postulate of the writers listed at the end of 2.4.1.1.

Apparently, these writers are misled by comparison of total extraction of coal seams with room-and-pillar mining of potash beds. There can be no doubt of temporary overburden load concentration on remnant pillars in a totally extracted coal seam. However, in a room-and-pillar potash mine where the regular pillars support the full overburden load there is simply no overburden load available for transfer to remnant pillars.

This writer cannot see any need for further discussion of postulates which lack common sense; the reader is referred to 2.1.2.4.

It is re-emphasized, however, that overburden load is transferred to remnant pillars and/or other abutments around mined-out areas of limited extent if and when stress relief creep zones overlap in pillars with inadequate w/h ratios.

Overburden load transfer to abutments around mined-out carnallite panels at Merkers created the preconditions for the 1958 rockburst, as had been the case at the Wintershall-Heringen mine in 1953, see 2.3.

It is also re-emphasized that the 100-m roof salt sequence above the potash mines in the Werra district must not be considered as an elastic plate that contributed to load transfer, as postulated by SPACKELER et al. (1960) with reference to HÖFER (1958c), see 2.3.4.

Sufficient data to show these relationships are published. Unfortunately, it is another tedious procedure to extract relevant data from dozens of publications which contradict each other frequently.

2.4.1.3 Gas outbursts significant, but ignored

The development of the Merkers mine since the beginning of this century reflects the geological conditions and the temporary demand for pure carnallite during the 1930's, see 2.3. Characteristic geological features are related to the Tertiary volcanism which affected the two potash beds as shown in more detail in I/2.4.3.

Outbursts of CO_2 gases had most severe effects on the development of the Merkers mine. According to MÜLLER (1958), two outbursts in 1938 interrupted the development of the lower potash bed for 10 months. GIMM (1968) reports a delay of only 6 months, stressing that 11 miners were killed at the upper level while trying to escape the advancing CO_2 gases; the gas volume was estimated at 50 000 m^3.

This outburst on July 30, 1938, prompted the regulation that the potash mines of the Werra district must be evacuated prior to setting off the blasts electrically from the surface.

The difference in the reported repair times of 10 and 6 months, respectively, results from the latter writer's failure to mention the second gas outburst. It occurred on Dec. 31, 1938, when mining resumed after repair of the damage caused by the first outburst. The second outburst liberated an estimated 200 000 m^3 of gases which pushed out of the mine through the mine shafts (MÜLLER, 1958).

HARTWIG (1954) shows the exact dimensions of the cavities created by the two gas outbursts. Fig. 2-27 demonstrates the irregular shapes of such cavities; it also shows how deep into the roof such outbursts may penetrate, i.e., how thick local accumulations of carnallite may be.

Needless to say that gas outbursts have detrimental effects on the supporting capacity of pillars - if at all such remnants between gas outburst cavities as shown in Fig. 2-27 can be called pillars. Such remnants may exceed 15 m in height; they cannot provide any effective resistance against the convergence of areas with numerous outburst cavities.

It also goes without saying that areas with numerous gas outburst cavities cannot provide any effective support of the overburden. The behavior of the overlying sandstone formation and the development of the mine determine whether or not the prerequisites for sudden tensile failure of the sandstone develop. As long as the spans of mined-out areas with numerous gas outbursts do not exceed certain dimensions, the sandstone formation may exhibit plate-like behavior.

The existence of fracture zones makes it impossible to calculate the spans at which tension in the sandstone plate may result in tensile failure; the reader is referred to 2.3.4.

DUCHROW (1958) recognized the serious rockburst danger caused by gas outbursts, confirming that ourbursts frequently terminate prematurely because of salt accumulations in the outburst cavities, see I/4.5.1 The premature termination of an outburst is followed by another outburst when mine openings advance; Fig. 2-27 is a typical example of these relationships.

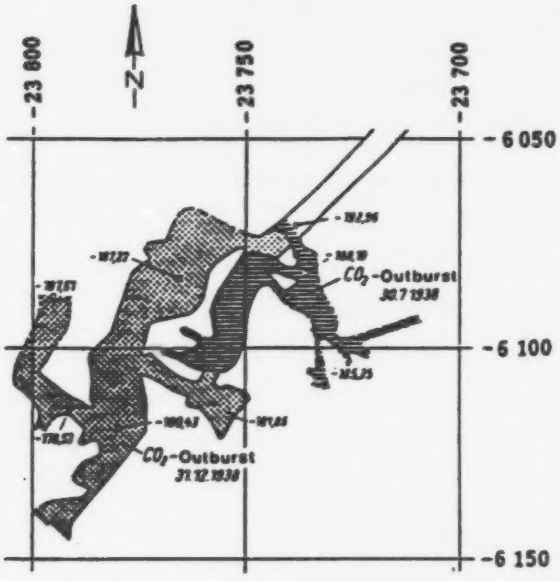


Fig. 2-27: Gas outburst cavities at Kaiseroda II/III, Merkers potash mine in 1938 (after HARTWIG, 1954; Abb.5); elevations in metres below mean sea level, survey grid 50 m.

DUCHROW (1959), referring to HARTWIG (1954) and to his own investigations, stresses particularly that the actual dimensions of outburst cavities frequently escape detection. The writer concludes that most outburst cavities are interconnected, leaving hardly any pillars which could possibly contribute to overburden support. The writer considers gas outbursts as "a decisive cause of rockbursts."

This writer fully agrees with these statements. DUCHROW (1964), however, changed his quoted statement in favor of hypotheses promoted particularly by HÖFER (1958c), SPACKELER et al. (1960), and GIMM and PFORR (1961). DUCHROW gives no reason why he changed his 1959 statements to the contrary, but emphasizes the economic advantages of gas outbursts; this may indicate why safety considerations were sacrificed.

It is not possible to assess more precisely the role of gas outbursts in creating the preconditions for the 1958 rockburst. SPACKELER et al. (1960) and GIMM and PFORR (1961) completely ignore gas outbursts. However, GIMM (1968) stresses that 43 major gas outbursts occurred in the Merkers mine from 1960 to 1965, see Table I/4-VII (mine No. 3 is the Merkers mine). Maps to show the locations of gas outburst cavities are not published.

The 1958 rockburst may have been triggered by gas outbursts; according to GIMM (1968), the mine was filled with gases after the rockburst.

For further geological details, the reader is referred to HOPPE (1960) who stresses particularly the alterations of the lower potash bed at Merkers. Gas outbursts apparently were too numerous to be shown on mine maps; however, the writer presents some typical detail maps.

The undisputed fact that numerous gas outbursts occurred particularly in the lower potash bed at the Merkers mine must be considered in calculations of theoretical pillar loads as published by HÖFER and KNOLL (1971) and MENZEL (1972). The results of the academic exercises of these writers cannot be accepted because elasticity theories are used in arriving at pillar strengths. The writers ignore stress relief creep; however, it is acknowledged that they recognize the significance of the height of pillars in their appraisal of potential pillar failure.

Needless to say that the creep deformation of high carnallite pillars must not be neglected in theoretical calculations of pillar loads;

considerable overburden subsidence is required to reload stress-relieved carnallite pillars. The reader is referred to 2.2.2; in addition the following critical assessment of so-called briquetting experiments should be borne in mind.

2.4.1.4 Questionable "briquetting" experiments

DREYER (1974a) and other writers postulate that briquetting resulted in decreasing rates of underground subsidence after the 1958 rockburst. The recompacted pillar material is believed to have regained unlimited strength.

Briquetting may take place in the laboratory when model pillars are crushed between the platens of powerful loading machines. Such loading conditions are similar to the reloading of mine pillars crushed by sudden tensile failure of the sandstone formation above German potash mines.

MOHR (1955) seems to be the first writer to postulate that mine pillars loaded in excess of their fracture strength continue to provide support as shown in Fig. 2-28A. The writer refers to sylvinite pillars in the upper potash bed at the Wintershall-Heringen mine; his explanation is presented in literal translation as follows(l.c. p. 1216):

Area a is characterized by elastic deformation proportional to the load increase.

In area b, the deformation is no longer proportional as the material exhibits additional plastic deformation.

At point B the pillar fails; the failure is indicated by deformation under less load. The fractured pillar material is recompacted, in part elastically.

The failure load is re-established at point C. The area c is the area of fracture deformation.

In area d, the elastic part of the deformation decreases continuously if the area to which load is applied is wide enough; the material becomes incompressible. The deformation rate decreases rapidly with increasing load.

The supporting capability of pillars is exhausted at point B; the mine apparently is endangered if and when point B, the point of actual pillar failure, is reached. In order to re-establish overburden support,

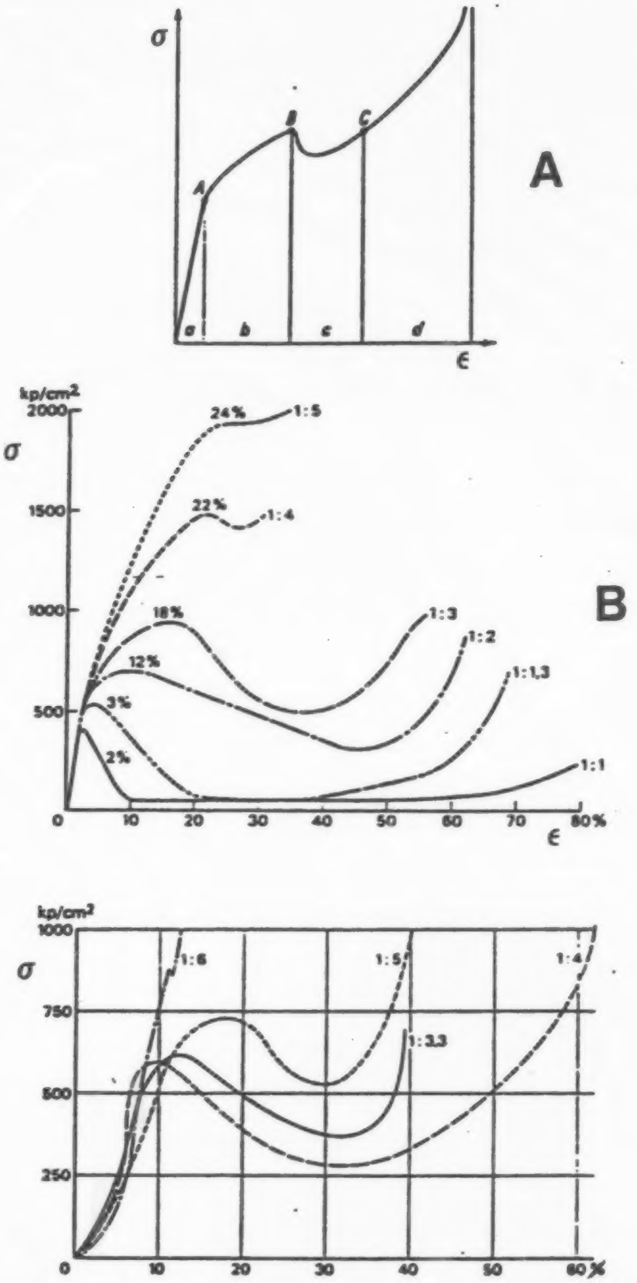


Fig. 2-28: Recompaction of pillar material after failure.
A. according to MOHR (1955, Abb.18) - sylvinite
B. according to UHLENBECKER (1971, Abb.26) - sylvinite
C. according to UHLENBECKER (1971, Abb. 27) - carnallite

See text for explanation and discussion.

corresponding overburden subsidence must take place between point B and the minimum value of supporting capability at approximately one third of the distance BC.

The writer stresses particularly the need for considerable overburden subsidence to recompact the pillar rubble.

If the overburden is capable of subsidence without failure in tension, the renewed supporting capability of the pillar rubble determines the safety of the mine.

If this is not the case, the capability of the overburden to bridge certain spans between abutments determines the safety of the mine workings.

Consequently, it is necessary to consider not only the supporting capability of the mine pillars; the deformability of the overburden must also be taken into consideration.

MOHR (1955) announced further research into the relationships between pillar loading and overburden behavior. However, others took over (DREYER, 1964-1974a; UHLENBECKER, 1968-1979), disregarding MOHR's statements and overemphasizing results of their briquetting experiments on model pillars.

The two writers used similar models made up of the pillar itself with roof and floor plates consisting of rocksalt. The pillars had square sections of 10 x 10 cm and various heights. Lateral deformation of the rocksalt roof and floor plates of the models was prevented by steel frames which are believed to simulate in-situ conditions. This is their fundamental error: as shown in Chapters I/4 and I/5 stress relief creep as well as reloading creep take place above and below mine pillars.

Some briquetting results selcted by UHLENBECKER (1971) show the need for considerable overburden subsidence to achieve recompaction of mine pillar rubble.

Fig. 2-28B shows the recompaction of the rubble of sylvinite models with heights from 2 to 10 cm, see Table 2-V for exact data. The following point are to be stressed:

(1) Loads of nearly 2000 kp/cm^2 had to be applied to crush the pillar model with the w/h ratio of 5 (height 2 cm). Such loads on sylvinite pillars are totally irrealistic at the depth of 800 m to which the

TABLE 2-V

Briquetting experiments on models (UHLENBECKER, 1971, p. 354). Models 10 x 10 cm square with roof and floor plates of rocksalt, see text.

Model height (cm)	Ratios h/w	w/h	Fracture strength (point B of Fig. 2-28A) Sylvinite ("Hartsalz") (kp/cm^2)	Carnallite (kp/cm^2)
10	1/1	1	400	n.a.
5	1/2	2	580	275
3.3	1/3	3	824	n.a.
3	1/3.3	3.3	1000	520
2.5	1/4	4	1480	580
2	1/5	5	1930	765
1.7	1/6	6	n.a.	1100
1.4	1/7	7	n.a.	1470

n.a. = not available. Composition of sylvinite not available. Carnallite contents up to 60%.

writer refers. The original load in virgin ground calculates as approximately 200 kp/cm^2. The load on mine pillars which fully support the overburden corresponds to the extraction ratio; with an extraction ratio of 66%, (l.c., p. 345), the maximum possible average pillar load calculates as 600 kp/cm^2.

(2) A 24% reduction in the height of the 2-cm model pillars was needed to arrive at point B of Fig. 2-28A. This means that corresponding surface subsidence must show above mine pillars with original heights of 2 m before pillar failure would occur. The extraction ratio is to be increased to 90% to arrive at the applied average pillar load of 2000 kp/cm^2. However, the writer (l.c., figs. 8 and 9) shows only 1 - 2 cm of maximum measured surface subsidence from 1954 to 1967.

(3) The writer stresses that only 50% of the small underground subsidence show at the surface a few weeks or months after the extraction of a given area.

This statement confirms that most of the intitial underground subsidence is attributable to stress relief creep. Subsequent surface subsidence rates of 3 - 5 mm/year clearly demonstrate that creep around the mine openings controls the overburden subsidence.

It is re-emphasized that creep at constant rates, even creep at increasing rates due to pillar reloading, is not indicative of impending pillar failure as postulated by numerous laboratory researchers. The reader is referred to Figs. I/5-2, I/5-16, and I/5-24 through I/5-26.

(4) At the maximum possible in-situ pillar load of 600 kp/cm^2, only models with heights exceeding 5 cm could be crushed. The 5 cm model required a 12% reduction in height at point B of Fig. 2-28A. Nearly 60% reduction in the original height was needed to arrive at point C where the recompacted model rubble shows the fracture strength.

(5) Tests on models with heights over 5 cm are meaningless with regard to sylvinite pillars which rarely exceed heights of 2.5 m. It should be noticed that the rubble of the model with the height of 10 cm regained the fracture strength only after 80% reduction of the original height, i.e., at the height of 2 cm.

Fig. 2-28C shows selected results of crushing tests on carnallite models. The writer fails to give any reason why results of tests on models with more representative w/h ratios are not shown. The reader is reminded of the fact that carnallite pillars in rockburst areas frequently exceed the height of 10 m. It should be noticed that the writer reports fracture strengths much higher than those reported by other writers, see I/3.3.2.

Particular emphasis is to be placed on the fact that the creep limits of carnallite are smaller than those of rocksalt and sylvinite. This fact should be borne in mind in the following discussion of much publicized briquetting experiments by DREYER who shows only one summary curve resembling Fig. 2-28A in numerous publications since 1964.

Some quotations (DREYER, 1972, pp. 301 - 326) may serve an additional purpose, i.e., to clarify some apparent errors in translation.

The writer's models were "I-shaped"; the roof and floor plates, consisting of rocksalt, were 20 cm thick, contrasting in this regard to UHLENBECKER's models with plates only a few centimetres thick. Both writers had the roof and floor plates "clamped by a thick steel frame which considerably inhibits lateral expansion"; this set-up is believed to represent "an approximation of the stress in-situ conditions."

The in-situ behavior of salt rocks around underground openings definitely cannot be approximated in this way, see I/4.3. However, DREYER's crushing experiments may be considered as representative of the loading conditions of mine pillar rubble after a rockburst in the overburden.

Apparently, the writer's interpretation is a literal translation of identical interpretations published in 1964 and 1967; to avoid any misrepresentation, the 1972 interpretation is quoted. The term "form factor" is replaced by the corresponding w/h ratio.

The term "various hard salt models from a uniform stratum in Hessen" (l.c., p. 307) means that the models were prepared from sylvinite ("hartsalz") of the upper potash bed in the Werra district which is called the Hessen seam. According to DREYER (1967, p. 97), the sylvinite was obtained from the Hattorf mine, i.e., the mine dealt with in UHLENBECKER's publications. Although pillar models with identical dimensions were crushed, none of the two writers mentions the other writer's experiments.

DREYER (1972, pp. 307/308) admits that his models with the height of 2 cm (w/h ratio = 5) could not be crushed; "the fracture in the model could not be seen directly and unambiguously, but it could be recorded on the basis of the irregular vibrations in the readings of the testing machine."

As shown in Fig. 2-28, the distance between the platens of the testing machine is to be reduced considerably to recompact the rubble of higher models.

The writer (l.c., p. 308) expects a similar behavior of mine pillars; with w/h ratios better than 4, "which is the critical limit of the investigated hard salts; a catastrophic pillar break should not be feared when the fracture limit is reached, only smaller relaxation breaks."

A correct translation from DREYER (1964, p. 162, or 1967, p. 99) should read as follows: mine pillars with the w/h ratio of 5 are expected to exhibit the behavior of the models with the w/h ratio of 5; this appears to be the critical w/h ratio for the investigated sylvinite. Catastrophic pillar failure in the case of loading in excess of the compressive strength is not to be expected; however, some spalling off the free surface of the pillars may take place.

A correct translation of the next paragraph should read: in cases of smaller w/h ratios, the supported loads decrease until the loading platens are adjusted accordingly, i.e., until the decreasing distance between the loading platens results in recompaction of the crushed model. This results in increasing supporting capability of the crushed material. After failure, models with the w/h ratio of 1, i.e., with original heights of 10 cm, exhibit supporting capabilities next to zero; the height of the rubble decreases continuously to 2 cm. Then the recompaction of the rubble begins, and results in a corresponding increase in supporting capability.

This is the behavior shown in Fig. 2-28; in DREYER's curve, the height of the recompacted rubble is shown decreasing further to zero, and to negative values. Apparently, crushed material is pushed into the roof and floor plates which are 20 cm thick; UHLENBECKER's roof and floor plates are only a few centimetres thick, so recompacted rubble cannot be pushed as easily into roof and floor.

There is an extremely important difference between the described briquetting experiments and actual mining conditions in the case of pillar failure due to sudden excessive loading: in mined-out room-and-pillar panels, the material which fell off pillars due to spalling cannot disappear. The extraction ratio determines when point C of Fig. 2-28A is reached. With the extraction ratio of 2/3, the pillar material is fully recompacted at 1/3 of the original pillar height.

Adequately designed mine pillars do not fail by fracturing as forced upon models in briquetting experiments. Stress relief creep and reloading creep may lead to complete closure of mine openings within relatively short periods of time, see I/5.2.

As carnallite is known to creep more easily than sylvinite and rocksalt, less time is required for complete closure of openings in carnallite and of mined-out carnallite panels, provided that subsiding overburden keeps the carnallite pillars or their rubble fully loaded according to depth and extraction ratio.

DREYER (1974a) claims that he inspected the rockburst areas of both the Wintershall-Heringen and the Merkers mines; apparently the recompaction of pillar rubble had not yet taken place at the time of inspection.

It is shown in 2.4.3 that, at least above one "destroyed" area in the lower potash bed at Merkers, only 0.6 m of underground subsidence were measured after the 1958 rockburst.

As criticized repeatedly, laboratory researchers frequently assume excessive loading of mine pillars which show superficial spalling. In many cases such pillars are affected only by stress relief creep. At the Merkers mine, additional spalling was caused by frequent gas outbursts, see 2.4.1.3. Apparently, the widespread spalling which may have taken place over many decades led to premature conclusions.

2.4.1.5 No "critical depth"

GIMM (1968, p. 250) shows the creep rates of carnallite pillars increasing abnormally below the "critical depth" of 500 - 600 m. Similar hypotheses are published by other writers, particularly by HÖFER (1958a and other publications). The subject matter is dealt with in Chapter I/5; the postulate of abnormal increases in carnallite creep rates below a "critical depth" is inacceptable.

2.4.2 Geology and mining situation

The mining situation at the time of the rockburst is summarized as follows on the basis of the schematic mine maps shown as Figs. 2-25 and 2-26.

In the first place, an apparent contradiction in publications is to be clarified. GIMM (1968, p. 242) reports "concentrated extraction" in progress in both the upper and lower potash beds. The same writer (l.c., p. 243) also reports that extraction mining in the upper potash bed was terminated 2 years prior to the rockburst. The latter statement applies only to mined-out areas reported as destroyed by the rockburst, see Fig. 2-29, which is attributed to a non-identified paper by DUCHROW.

The room and pillar dimensions in the sylvinitic upper potash bed were as follows: room width 20 m, height 1.8 - 2.4 m, pillar width 10 m, pillar length 250 m with ventilation breakthroughs at distances of 30 - 50 m. In some areas of limited extent, carnallite overlying the sylvinite seam was extracted; exact data on room heights in these areas are not available.

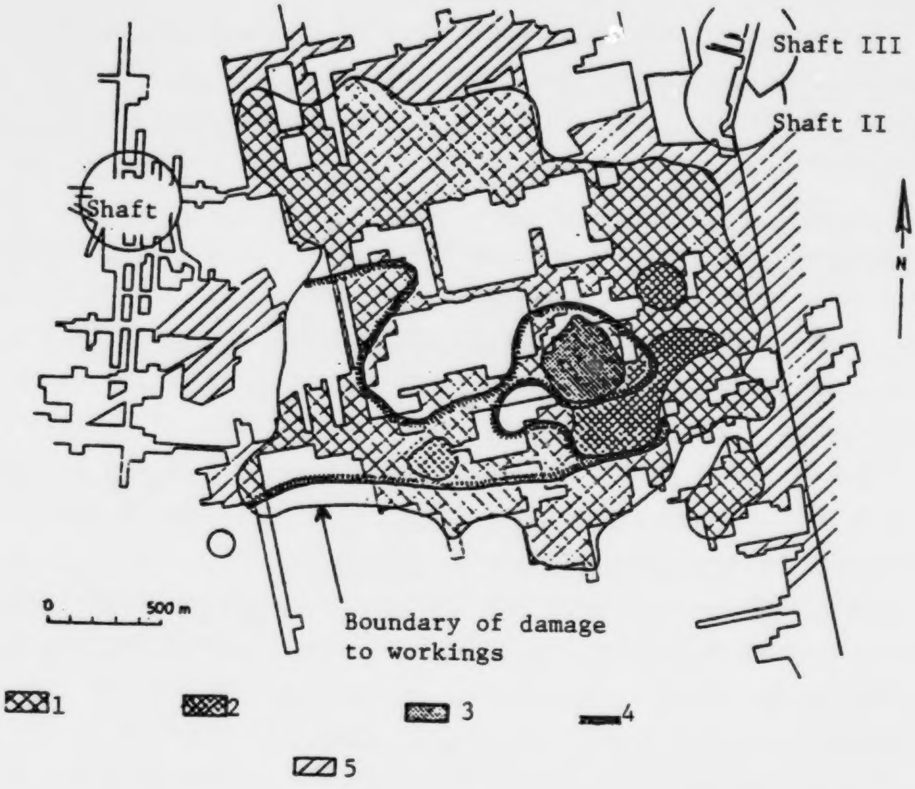


Fig. 2-29: Schematic mine plan - upper level - of the potash mine 'Ernst Thälmann' II/III, Merkers; showing the degree of damage to workings due to the rockburst in 1958 (after DUCHROW, 1959 in GIMM, 1968; Bild 4/89)

1 - spalling off walls
2 - severe damage to pillars
3 - pillars destroyed
4 - boundary of area where a carnallite bed above the normal sylvinite was extracted
5 - mined out room-and-pillar area

Fig. 2-29 shows maximum spans of less than 300 m for areas in the upper potash bed where carnallite was mined. This span is too small for significant affects on the plate-like behavior of the 500-m sandstone formation above the salt sequences.

The damage attributed to the rockburst is described as particularly severe in the lower potash bed. The following geological situation is stressed with HOPPE (1960, p. 80): in the southwestern part of the mine, local carnallite accumulations in the lower potash bed are up to 35 m thick.

Gas outburst cavities and the great thicknesses of extracted carnallite make large remnant pillars in the lower potash bed most significant. These remnant pillars apparently provided abutments for the overburden. As no surface subsidence was detected prior to the rockburst, the sandstone overburden apparently was behaving like an elastic plate supported by virgin ground, by large remnant pillars in the central mined-out area of the lower potash bed, and by brine pressure in the dolomite formation underneath the sandstone.

GIMM (1968, p. 246) provides fairly exact data on the extraction of the largest remnant pillar in the central area of the lower potash bed, see Fig. 2-26. In 1955, the remnant was 1300 m long and 400 - 700 m wide; its western part was mined from 1955 to 1958. At the time of the rockburst, the length of the remnant had decreased to 600 m, the width was 400 m.

The decrease in length of the remnant means that the span of the mined-out area along the safety pillar against the Dietlas mine increased by approximately 700 m over few years, see Fig. 2-29. Apparently, the relatively high carnallite pillars in this area could not provide any effective support of the overburden, so the tension in the sandstone formation increased until it resulted in the rockburst on July 8, 1958.

2.4.3 Subsidence

2.4.3.1 Underground subsidence

GIMM and PFORR (1961) give some information on underground subsidence in "destroyed" areas. Measurements of underground subsidence in the incline from the upper to the lower extraction level are of particular interest.

At point 1 in the upper potash bed, the thickness of the rocksalt between the two potash beds is only 28 m (GIMM and PFORR, 1961, Fig. 42).

SPACKELER et al. (1960, p. 591) emphasize the relatively small thickness of only 30 - 40 m of the rocksalt between the two potash beds in areas considered as affected by the rockburst. The normal thickness of the rocksalt is given as approximately 60 m.

Fig. 2-31 (GIMM and PFORR, 1961; GIMM, 1968) is supposed to show line DE in Fig. 2-30. In order to eliminate some apparent errors in the numbering of the survey points, the numbering was changed to point 1 at the NW end and point 24 at the ENE end of the survey line.

Fig. 2-31 shows the NW - SE part of the survey line from point 1 to point 10; it reveals some unacceptable oversimplifications in Fig. 2-30 which are to be corrected in the first place as follows:

(1) From point 1 at the upper extraction level to point 6 at the lower level, the incline follows the NW-SE direction as shown in Fig. 2-30. However, from point 6 to point 8, i.e., at the lower extraction level, the survey line runs exactly N-S as shown in Fig. 2-31.

(2) The exact elevations of the survey points are given in the uppermost diagram of Fig. 2-31. The diagram clearly shows the slope of the incline from point 1 to point 6 smaller than the slope of the roadway in the lower potash bed from point 6 to point 8.

(3) Fig. 2-30 shows the western boundary of the largest "destroyed" area in the lower potash bed underneath point 3; the eastern boundary coincides approximately with point 6 at the lower extraction level.

(4) The writers fail to explain why their Fig. 2-31 shows roof subsidence but no floor deformation for points 5 - 8, and particularly for points 5 and 6. Point 6 shows the maximum roof subsidence caused by the rockburst amounting to approximately 55 cm.

(5) GIMM and PFORR (1961, p. 74) emphasize that Fig. 2-31 is based on an initial survey in 1933 and just one survey after the rockburst in 1958. No measurements were made during the period of 25 years prior to the rockburst.

The question raised under (4) above can be answered with reference to a remark by SPACKELER et al. (1960, p. 590) which is presented in literal translation as follows: it is remarkable that all roadways in rocksalt above or below the potash beds were able to absorb the loading conditions created by the rockburst even in areas which suffered heavy destruction, provided that the thickness of the rocksalt between

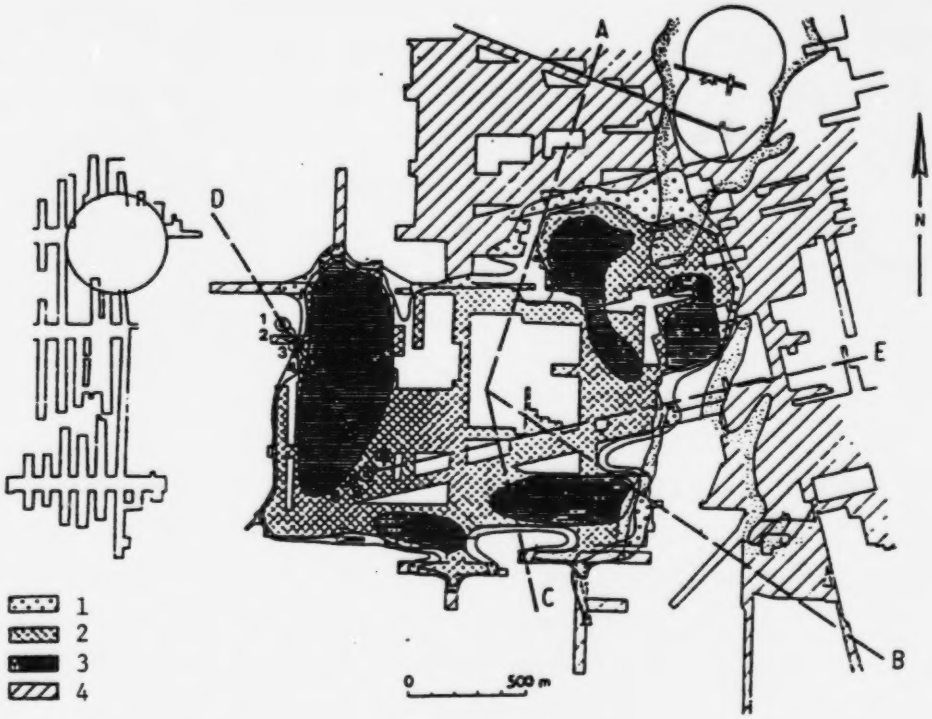


Fig. 2-30: Schematic mine plan - lower level - of the potash mine 'Ernst Thälmann' II/III, Merkers; showing the degree of damage to workings due to the 1958 rockburst (after GIMM, 1968; Bild 4/90)

1 - spalling off pillars
2 - severe damage to pillars
3 - pillars destroyed
4 - mined out room-and-pillar area

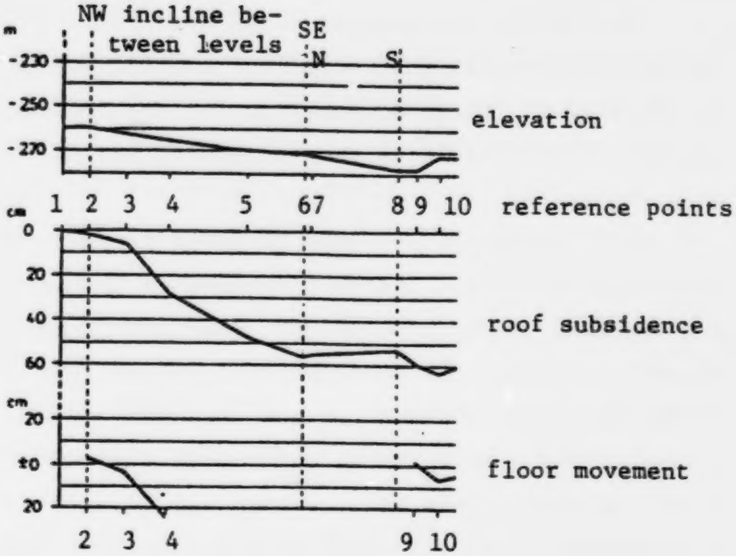


Fig. 2-31: Deformation in the incline between levels, 1933 to 1958 at Merkers potash mine (after GIMM and PFORR, 1961; Bild 44) for location of reference points see Fig. 2-30.

openings in the potash beds and the roadways exceeded 3 m.

In other words: the floor points 5 and 6 collapsed into the mined-out area. Apparently, the floor points 7 and 8 were not included in the survey because they were covered with rubble from roof collapse and spalling off the pillars.

The incline crossed the "destroyed" area at relatively small vertical distances; much more roof subsidence due to the rockburst must be expected if indeed splintering failure according to KVAPIL (1958) destroyed the underlying carnallite pillars as postulated by all writers referred to.

It is re-emphasized that 25 years elapsed between the two surveys shown in Fig. 2-31. The roof subsidence in the incline may be partly attributable to bed separation. However, this writer considers stress relief creep into the underlying mined-out area as the principal cause of the measured subsidences; gas outbursts as suggested by the geological situation may have enhanced deformations of the rocksalt above the mined-out area in the lower potash bed.

However, the salt cover of the upper extraction level remained impermeable; no water or brine inflows are reported.

The maximum subsidence of the roof of the incline was less than 60 cm and may be partly attributable to bed separation. This writer considers stress relief creep into the underlying openings in carnallite as the cause of the measured subsidences. The geological situation suggests that gas outbursts took place in the lower potash bed.

However, the salt cover of the mine remained impermeable; no water inflow is reported.

The SE-ENE portion of the original of Fig. 2-31 is not included in this text because of lack of sufficient information, particularly regarding the exact locations of the survey points with respect to opening intersections.

It may be emphasized that the visible effects of the rockburst did not extend across the basaltic zone shown south of the shafts 2 and 3, Fig. 2-30.

2.4.3.2 Surface subsidence

Results of surface subsidence measurements above the rockburst area are dealt with in various publications, e.g., GIMM and PFORR (1961) and GIMM (1968). The writers refer to unpublished papers; the published maps and profiles need many corrections.

There are some apparent errors in the numbering of the observation points (GIMM and PFORR, 1961, fig. 43). According to the writers (l. c., pp. 79 - 81), the survey lines were set up in 1956, and the last survey prior to the rockburst was made in August 1956. GIMM (1968, p. 247) reports that the last survey was made in 1955; this appears to be just a printing error which escaped correction.

According to GIMM and PFORR (1961, pp. 70 - 81), the first survey after the rockburst was made in September 1958. GIMM (1968, p. 248) reports that the first measurements after the rockburst were taken in July 1958. However, the surface subsidences shown for July and September 1958 are the same.

These contradictions could not be clarified. Also was it impossible to determine whether the first subsidences shown in the reference publications occurred instantly, and if so, where instant subsidence due to the rockburst took place.

Most writers claim that no surface subsidence could be detected prior to the rockburst. However, as shown previously, surface subsidence must take place if pillar failure due to excess loading is postulated; overburden subsidence is prerequisite for the reloading of stress-relieved mine pillars as shown in Chapter I/5.

In the case of elastic behavior of the overlying sandstone formation until it ruptures in tension, instant surface subsidence is to be expected, as documented for the 1940 and 1953 rockbursts, see 2.2.4 and 2.3.

The surface subsidence profiles shown for the 1958 rockburst are irrelevant in the interpretation of its mechanism because the survey lines are not located above mined-out carnallite areas, see Fig. 2-31.

Most survey points were located above remnant pillars in the upper potash bed and very close to remnant pillars in the lower potash bed. Accordingly, significant surface subsidence could not be measured. In addition, some mined-out areas in the lower potash bed were severely affected by gas outbursts, see 2.4.1.3. Apparently, some remnant pillars were left for this reason.

Summarizing this appraisal of published surface subsidence profiles, this writer agrees with numerous publications which claim that no relevant surface subsidence occurred prior to the rockburst in July, 1958. The apparent reason is that the survey lines are located above mined-out areas with normal pillars and remnant pillars. Spans of mined-out areas sufficient to cause significant bending of the sandstone formation were not reached. The stability of some areas was in jeopardy because of gas outbursts.

The typical subsidence trough which developed after the rockburst indicates the change in the behavior of the sandstone formation after its failure in tension. Over considerable length, the survey line is located in tension zones of mined-out areas where effective overburden support was missing due to gas outbursts.

GIMM and PFORR (1961, pp. 72-74) emphasize the significance of a basalt zone which was left as a remnant pillar. The writers emphasize that no underground damage was observed east of the basalt zone.

These observations suggest that the sandstone plate was torn apart along N-S fractures when the tension due to lack of adequate support in the mined-out area became excessive. Gas outbursts in both potash beds west of the remnant pillars may have contributed to the build-up of tension in the sandstone formation. The sudden rupture of the sandstone plate resulted in sudden loading of the stress-relieved pillars.

It is not suggested that the rupture of the sandstone plate at this location resulted in the first shock wave of the earthquake. The situation was worse at the western boundary of the mine where the mined-out area affected by gas outbursts and a wider span. However, it must be borne in mind that the final subsidence above large areas, in which indeed some carnallite pillars may have been destroyed, will reach several metres. This subject matter is discussed in the following.

2.4.4 Hypotheses changed to the opposite

GIMM (1968) gives questionable interpretations of the development of surface subsidence profiles; his curves are based on average surface subsidence rates for some years after the 1958 rockburst.

The writer (l.c., p. 249) believes in positive effects of the recompaction ("briquetting") of the destroyed pillars, see 2.4.1.4. This interpretation cannot be accepted. For the purpose of a detailed discussion, parts of the writer's text (l.c., pp. 243-251) are presented in literal translation.

Particular emphasis is placed on underground convergence measurements since 1930, see Fig. I/5-14. The writer claims: it is now known that the very small surface subsidences are attributable to

(1) favorable pillar dimensions at shallow depths around 400 m,
(2) almost exclusive mining of sylvinite with small thicknesses,
(3) relatively small spans of mined-out areas.

The following reasons for the development of unfavorable conditions prior to the 1958 rockburst are cited (l.c., p. 247): the strength and deformation characteristics of the mine pillars had changed due to increased carnallite extraction in the lower potash bed; the mining depth had increased from 300 - 400 m to 500 - 700 m; the extraction had been concentrated in certain areas; considerable thicknesses of carnallite were encountered and extracted; in general, the spans of mined-out areas had become larger; in addition, remnant pillars in the upper potash bed affected the extraction of the lower potash bed.

The latter statement is incorrect, see 2.4.1.2.

The writer (l.c., p. 247) continues stating that only scanty measurement data are available at the Merkers mine; for this reason, principles learned from measurements at other potash mines of the Werra district are used to characterize the displacements and deformations related to the 1958 rockburst.

It is re-emphasized that room-and-pillar mining with pillars which can be considered as stable structural elements and the total extraction of coal seams are two entirely different mining methods. If room-and-pillar mining results in overburden subsidence, it is due to creep deformation as shown in Chapter I/5. It has been known for many decades that the subsidence characteristics above room-and-pillar potash mines resemble the characteristics of subsidence due to total extraction, see Chapter 7.

Regarding the Werra potash mining district, German writers postulate that structural stability of the mine workings is achieved by proper pillar dimensioning (HÖFER, 1958a, c; SPACKELER, 1950, 1957; SPACKELER et al., 1960; GIMM and PFORR, 1961, 1964). This hypothesis apparently changed to the opposite; under certain conditions, overburden subsidence must be initiated to prevent rockbursts BAAR (1958, 1959a, b).

One important difference in the development of surface subsidence troughs above room-and-pillar salt mines and coal mines, respectively, must not be ignored: the limiting value of surface subsidence above coal mines may be reached within a few months after the extraction; above room-and-pillar potash mines, it may take many decades until the subsidence process terminates. In fact, this most important difference is confirmed in the following literal translation, with this writer's remarks in brackets, from GIMM (1968, p. 247): in the case of the 1958 rockburst at Merkers, large areas of the roof were left without support because of the sudden failure of the carnallite pillars (this theoretical postulate is based on the erroneous assumption of elastic behavior of carnallite, see 2.4.1).

It is assumed that subsidences prior to the rockburst were minimal. Observations made immediately after the rockburst showed the maximum increase of 45 cm of surface subsidence since the last preceding measurements in August 1955 (this appears to be a printing error; the respective figure shows August 1956 as the month of the last measurements prior to the rockburst on July 8, 1958).

Approximately 70% of the subsidences measured over 8 years occurred immediately after the rockburst. One-half year after the rockburst, 84% of the measured subsidences had already taken place. Since that time, the subsidence rates are decreasing continuously, approaching an ultimate state; mining at the periphery of the rockburst area ceased after the rockburst.

The angle of draw is averaging 36°. The maximum subsidences measured after the rockburst are directly related to mined-out areas in which the pillars had been destroyed by splintering failure.

These statements are in need of corrections. First of all, it is emphasized that the "ultimate state" of subsidence above the 1958 rockburst area is subsidence at constant rates. This is clearly shown by the curves in the respective figure; the limiting value of subsidence, i.e., the ultimate state of deformations will not be reached before centuries have passed.

With the maximum constant subsidence rate of 7.3 mm/year (Table 2 - V) and the extraction ratio of 50% in mined-out areas with long pillars 6 m high, the limiting value of surface subsidence calculates as 3m. As only ½ m of surface subsidence occurred until 1964, 2.5 m are left to take place. At the yearly rate of 7.3 mm, it takes 182 years until the limiting value is reached. If only about 2/3 of the underground subsidence show at the surface because of remaining loosening, it still would take more than a century.

If "briquetting" were indeed the only possible process to cause the subsidence rates to decrease, it could not become effective before centuries had passed. Another mechanism must be controlling the subsidence rates over considerable periods of time; two possibilities are to be considered. If indeed some pillars were destroyed, slow creep deformations out of abutment zones, similar to Figs. I/5-22 and I/5-13A, could be the mechanism that controls the subsidence rates.

There are reasons to assume that most of the pillars were not destroyed; in this case, Fig. I/5-13A would apply. It should be mentioned that roof creep deformations resembling the floor deformations shown in these figures are to be expected as the immediate roof at the Merkers mine consists of rocksalt; the reader is referred to Figs. I/4-6 and I/4-13 which show the development of stress relief creep zones.

There is reason to assume that the lack of published data reflects another problem: mine design and development principles introduced after the 1958 rockburst apparently resulted in the 1961 rockburst at the same mine, see 2.5.

2.4.5 Seismic data

The surface perceptibilities of the 1958 rockburst are shown in Fig. 2-32. The area including grade 3 intensities of the Mercalli-Sieberg scale covers 1200 km^2, comparing with 1500 km^2 on occasion of the 1953 rockburst, see Fig. 2-14.

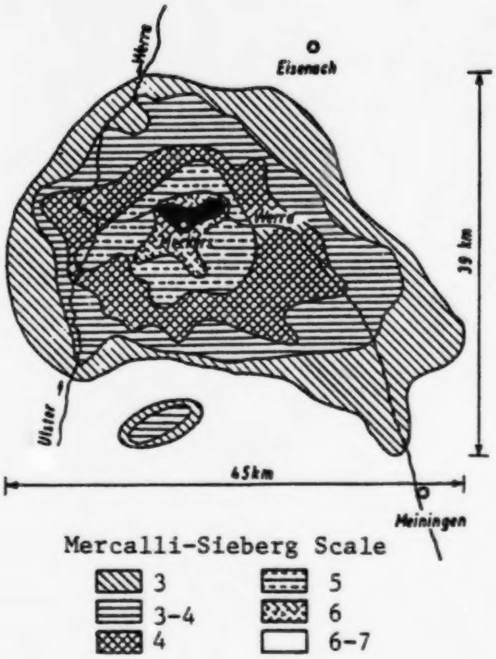


Fig. 2-32: Seismic intensity of the 1958 rockburst at Merkers potash mine (after SPONHEUER, 1959 in GIMM, 1968; Bild 4/91); for an explanation of the Mercalli-Sieberg Scale see Table IV.

At Merkers, the maximum intensity at the epicentre was 6.5 (SPACKELER et al., 1960, p. 585); it was 8 above the Wintershall-Heringen mine in 1953. This explains the considerable difference in surface damage; the 1953 rockburst was much stronger than the 1958 rockburst. A comparison of the areas with grade 4 intensities shows this statement even more justified.

The 1958 rockburst consisted of the main shock and 7 aftershocks. Seismic observatories at distances up to 2000 km registered the rockburst as an earthquake with the focal depth of only 0.5 km (SPACKELER et al., 1960, p. 585; MARTIN, l.c., p. 597).

This sequence of shocks postulated by KVAPIL and PFORR (1960, discussion to SPACKELER et al., 1960, pp. 600/601; 1961, appendix to GIMM and PFORR, 1961, pp. 182-190) appears questionable as it is based on the erroneous assumption of elastic storage of energy in carnallite pillars. It is re-emphasized that fracturing from the edge of the mined-out carnallite area to the surface cannot have taken place as no water inflow occurred.

The seismic data show hypotheses of chain-reaction-type of failure of carnallite pillars inconclusive. The main shock apparently was caused by tensile failure of the sandstone formation near the western edge of the mine, as this area had the largest span among mined-out carnallite areas in the lower potash bed. The aftershocks may have been caused by resulting adjustments in the sandstone formation, as subsidence was no longer prevented by plate-like behavior.

2.4.6 Rockburst mechanism - summary

This writer's interpretation of the mechanism of the 1958 rockburst is summarized as follows:

(1) The assessment of damages attributed to the rockburst was biased by the belief that spalling off mine pillars indicates pillar failure. Extensive spalling occurred prior to the rockburst, particularly in mined-out areas with large gas outburst cavities.

(2) Pillar failure, if any, took place in relatively small mined-out areas in thick carnallite; the pillars had suffered heavy spalling due to stress relief creep and/or gas outbursts.

(3) In the upper potash bed, room convergence measured over 25 years

prior to the rockburst amounted to 5-31 mm in sylvinite ("hartsalz") and 19-96 mm in carnallite in relatively small mined-out areas. Elastic behavior of a thick sandstone formation above the salt sequence prevented overburden subsidence.

(4) Normal sylvinite pillars support the full deadweight of the overburden; the concept of overburden load transfer to remnant pillars is applicable only to relatively small mined-out areas in thick carnallite.

(5) Measured underground subsidences of an incline from the upper to the lower potash bed are particularly significant. Up to 60 cm of underground subsidence occurred over a time period of 25 years, including some time after the rockburst. These underground subsidences were not caused by the rockburst, but by stress relief creep into underlying openings in thick carnallite.

(6) In some mined-out areas in the lower potash bed, large gas outburst cavities left hardly any pillars. The exact location of such gas outburst areas is not known; there is reason to assume that gas outburst areas are those identified as areas of maximum pillar destruction.

(7) Weakening of pillars due to large interconnected gas outburst cavities constitutes the main cause of the rockburst. The sandstone overburden above such mined-out areas continued to exhibit elastic behavior; abutments were provided by large remnant pillars and/or virgin ground.

(8) All writers dealing with the rockburst report no surface subsidence prior to the rockburst. Elastic behavior of rocksalt sequences cannot be invoked in explanations of the lack of surface subsidence. However, disposal brines in a dolomite formation contributed to overburden support.

(9) Theoretical calculations of the span required to initiate subsidence of sandstone plates are merely speculative because the sandstone formation is fractured, preferably in the N-S direction. The location of fractures cannot be predicted with certainty. Surface fractures observed after the rockburst apparently indicate pre-existing fractures intersecting the sandstone formation.

(10) The facts summarized above indicate that most of the reported underground damage cannot be attributed to the rockburst. Extensive

spalling occurred prior to the rockburst, particularly in mined-out areas affected by gas outbursts. The intensity of the 1958 rockburst did not reach the intensity of the 1953 rockburst at the Wintershall-Heringen mine.

2.5 MERKERS POTASH MINE, 1961

2.5.1 Mining Situation

There is reason to assume that the 1961 rockburst at the Merkers mine was caused by the application of erroneous hypotheses in pillar dimensioning. The continuing promotion of such erroneous hypotheses makes it necessary to clarify the subject matter.

The reader is reminded of the following facts discussed in detail in the preceding section:

Mining discontinued in areas considered damaged by the 1958 rockburst. Extraction resumed east and southeast of a basalt zone south of the mine shafts; large remnant pillars left in the lower potash bed are shown in Figs. 2-26 and 2-30.

The further development of the surface subsidence above the rockburst area is not dealt with in publications; however, there are reasons for the assumption of constant subsidence rates.

No surface subsidence was measured at points located above the eastern part of the basalt zone. N-S fractures in the sandstone formation may have prevented the eastward extension of the surface subsidence trough.

The sandstone formation above the developing new extraction area apparently was behaving like an elastic plate until the mined-out area reached spans sufficient to cause tensile failure of the sandstone. In all probability the sandstone failure took place above the edge of the basalt zone where pre-existing fractures in the N-S direction reduced the tensile strength.

2.5.2 New designs introduced after the 1958 rockburst

According to GIMM and PFORR (1961, Fig. 99), a panel-and-pillar design was introduced at Merkers after the 1958 rockburst. The design is discussed in detail in I/5.4; it calls for panels of 8 long rooms separated by pillars with the design width of only 5 m. With rooms 16 m wide the panel span calculates as 163 m. However, the writers also show room widths of 15 m, so the panel span would be only 155 m. Apparently, the error escaped correction prior to the publication of the plan. The length of the panels is given as 254 m.

The panels are separated by 76-m barrier pillars for stable structural support of the overburden. Some theoreticians believe in stable stress arches from barrier pillar to barrier pillar (HÖFER, 1958a) others postulate near-elastic behavior of the overlying rocksalt (SPACKELER et al., 1960, with reference to HÖFER, 1958c). The latter postulate was dropped when the new panel-and-pillar design resulted in unexpected subsidences in the upper potash bed (PFORR and HOTTEWITZ, 1967; GIMM, 1968).

The unexpected subsidences were apparently caused by stress relief creep. The described panel-and-pillar design was changed; see Table 2-VI. The writers fail to mention barrier pillars between panels; apparently, 9-m pillars were considered stable, and it was theorized that barrier pillars were not needed.

The lack of reliable information on the actual room and pillar dimensions and on the mine development in the 1961 rockburst area disallows any further discussion.

However, it is re-emphasized that intensive stress relief creep is to be expected in panels with the room and pillar dimensions listed in Table 2-VI. Gas outbursts probably also contributed to the removal of overburden support.

2.5.3 Mechanism of the rockburst

The situation shown in Fig. 2-17 is re-emphasized; the writers who describe the development of the subsidence trough after the 1958 rockburst postulate the tension zone above the large remnant pillars between the damaged area and the new extraction area.

Lack of adequate overburden support east of the remnant pillars resulted in tension in the sandstone formation as it was drawn into the new extraction area, i.e., in the direction opposite to the draw into the 1958 rockburst area. This is the situation which is considered

TABLE 2-VI

Merkers potash mine: Room and pillar dimensions in the lower potash bed.

Source	Room width (m)	Height (m)	Pillar width (m)
Spackeler et al.(1960, p.585)	16	2 - 10	10
Gimm and Pforr (1961, p. 68)	16	2 - 10	10
Gimm (1968, p. 243)	16	2 - 10	10
Höfer and Knoll (1971, p. 71)	15-16	n. m.*	10-12
Menzel (1972, p. 352)	15-16	4 - 10	10-12
Gimm et al.(1972, p.607)	up to 25**	up to 40***	n.m.*
Dreyer (1974a, p. 116)	16	2 - 10	10

* not mentioned **roof span in local carnallite accumulations

***room and pillar height in local carnallite accumulations particularly dangerous in cases where pre-existing fractures run parallel to the edges of remnant pillars. If no surface subsidence can be detected, i.e., if the sandstone formation exhibits elastic behavior above the developing new extraction area, failure in tension can take place at any time; there is no possibility of calculating the required span as the location of pre-existing fractures is not known.

Apparently, the sandstone formation was torn apart rather easily when tensile stress built up above the new extraction area east of the basalt zone; according to Table 2-I, the new extraction area measured only 0.2 km^2 at the time of the rockburst.

The promotion of untenable hypotheses which postulate the storage of elastic energy in carnallite pillars must be stopped as carnallite is the potash ore that has long been known for deforming most easily by creep under normal mining conditions. This statement applies particularly to DREYER (1974a) whose reports are to be corrected as follows:

(1) (l.c., p. 100): the writer reports that the 1958 rockburst at Merkers destroyed an area of 2.8 km^2 only in the upper potash bed. In fact, hardly any damage in the upper potash bed can be attributed to the rockburst, see 2.4.1.1.

(2) (l.c., p. 100): the 1961 rockburst is reported to have destroyed an area of 2 km^2 in the lower potash bed only. All other writers report damage to an area of 0.2 km^2; there is reason to assume that gas outbursts rather than the rockburst caused most of the damage.

(3) (l.c., pp. 120-122): the writer presents a literal repetition of his extremely dangerous hypotheses presented for the first time in the discussion to SPACKELER et al. (1960); DREYER postulates small pillars in carnallite to enable sufficient creep and to prevent elastic energy storage. The reader is referred to I/3.3.2.

(4) (l.c., p. 123): the writer claims that the following recommendations published by PFORR and HOTTEWITZ (1967) are based on his own hypotheses mentioned under (3). The recommendations are:

(a) To reduce the extraction ratio for better supporting capability of carnallite pillars. The writer ignores the fact that extensive stress relief creep of high carnallite pillars cannot be prevented at depths in excess of 700 m; in the 1961 rockburst area, the excavation of only one room-pillar-room unit with the width of 37 m in the lower potash bed resulted in unexpected subsidence in the upper potash bed. PFORR and HOTTEWITZ (1967, p. 261) postulate extraction of only 20% of carnallite beds.

(b) To avoid remnant pillars. This is a typical ivory-tower postulate; barren areas in a potash bed cannot be mined just for the sake of questionable postulates which frequently lack common sense, see 2.4.1.2.

(c) To leave "soft edges" of mined-out areas; the term, apparently introduced by GIMM and PFORR (1961), means that the supporting capability of pillars should be increased systematically toward the edge of mined-out areas. The writers are confused by inadequate comparison of room-and-pillar mining and total extraction, see 2.4.1.2.

(d) To mine the upper potash bed in advance. PFORR and HOTTEWITZ (1967) and GIMM (1968) postulate exactly the opposite. The extraction front in the lower potash bed should travel 200 - 300 m ahead of the extraction front in the upper potash bed.

(e) To backfill mined-out rooms for improved pillar stability. The standard method of backfilling used in German room-and-pillar potash mines is to pipe hot refinery waste hydraulically into mined-out panels; this practice has long been recognized as dangerous because the temperature increase results in increased creep deformation. With reference to I/5.3.2 and to Chapter 5, the reader must be warned against the implementation of this recommendation under certain geological conditions.

(5) To evacuate the mines prior to blasting. As outlined in 2.4.1.3, the potash mines in the Werra district are evacuated because of the possibility of huge gas outbursts.

2.6 UNTERBREIZBACH POTASH MINE (SÜNNA EARTHQUAKE), 1975

2.6.1 Lack of reliable data

The strongest earthquake on record in Germany since 1911 was caused by potash extraction in the Unterbreizbach mine on June 23, 1975. The epicentre was located near the town of Sünna. Possibly this earthquake will be referred to as the Sünna earthquake in statistics and publications. In this text, it is called the Unterbreizbach rockburst.

There are reasons to assume that the rockburst was caused by the application of erroneous hypotheses in the development of the Unterbreizbach potash mine (Vol. 1, pp. 2,61,74,81,221).

The second shaft of the Unterbreizbach mine was sunk during the early 1960's, as described in detail by GIMM (1968). The contour lines on a map published by HOPPE (1960, Fig. 2) indicate the elevations of the top of the dolomite formation into which wastes brines are disposed, see Fig. 2-24. This disposal formation was encountered at the depth of 610 - 630 m in the No. 2 shaft of the Unterbreizbach mine (GIMM 1968, p. 292). The contour lines show the top of the dolomite formation at the same depth underneath the town of Sünna, outlining a syncline with the axis emerging to the north.

The depth to the upper potash bed in the rockburst area is approximately 800 m.

The thickness of at least 800 m of the overburden in the 1975 rockburst area is stressed for the following reasons: only one publication dealing with the rockburst could be considered (LEYDECKER, 1976). The writer and the editor of the respective periodical were informed of several errors in the reference publication. This writer suggested that the errors be corrected in the same periodical. However, the correction was refused, so the errors are corrected here in the first place.

(1) (l.c., pp. 271/272): Potash mining in the Werra district began near the end of the last century. The series of heavy rockbursts (earthquakes) caused by potash mining began in 1953, see 2.3.

(2) (l.c., p. 272): Rockbursts occurred only above mined-out areas with carnallite thicknesses up to, and exceeding, 10 m.

(3) (l.c., p. 272): The mining depth of 300-600 m is correct only with respect to the 1953 event; the following events were caused by carnallite extraction at depths of 700 - 800 m.

(4) (l.c., p. 272): It may be correct that SPONHEUER et al. (1960) considered the sudden settlement of the overburden as the cause of the two earthquakes in 1953 and 1958. There are a number of previous publications in which tensile failure of the sandstone formation is

considered as the cause of these events, as shown in this text. The writer fails to mention that most writers consider the failure of carnallite pillars as the cause of these earthquakes, the seismic energy being stored in high carnallite pillars and being released in a chain-reaction of pillar failure.

(5) (l.c., p. 276): The mining depth underneath the town of Sünna is not 600 m, but at least 800 m, as shown above.

An approximate outline of the lease of the Unterbreizbach mine can be found on maps published by various writers referred to in this text.

The Unterbreizbach mine is known as the mine with the greatest number of gas outbursts among the potash mines in the Werra district, see Table I/4-VIII; the mine No. 1 is the Unterbreizbach mine. The role of gas outbursts in creating the preconditions for severe rockbursts is reemphasized with reference to 2.4.1.3.

The following text is based on the publication by LEYDECKER (1976).

2.6.2 Seismic data

The macroseismic intensities shown in Fig. 2- 33 are determined according to the Medwedjew-Sponheuer-Karnik scale with 12 degrees of intensities. The intensity II was observed at the distance of approximately 250 km. Particularly the upper levels of high-rises were affected, e.g., in Frankfurt/Main and Cologne, and had to be evacuated temporarily.

The writer (l.c., p. 274) emphasizes that the intensity III was observed at distances up to 100 km. A comparison with Figs. 2- 23 and 2-33 shows the outer boundary of grade IV intensities following the same pattern on all occasions of severe rockbursts. The Unterbreizbach rockburst occurred approximately 12 km south of the location of the Wintershall-Heringen rockburst in 1953. The northern boundary of the grade IV intensities apparently reflects the difference.

The southward shift of the 1975 boundary can be considered indicative of the same intensity of approximately VIII at the two epicentres.

In fact, LEYDECKER (l.c., p. 272) reports surface damages to buildings in the town of Sünna which appear to resemble those reported

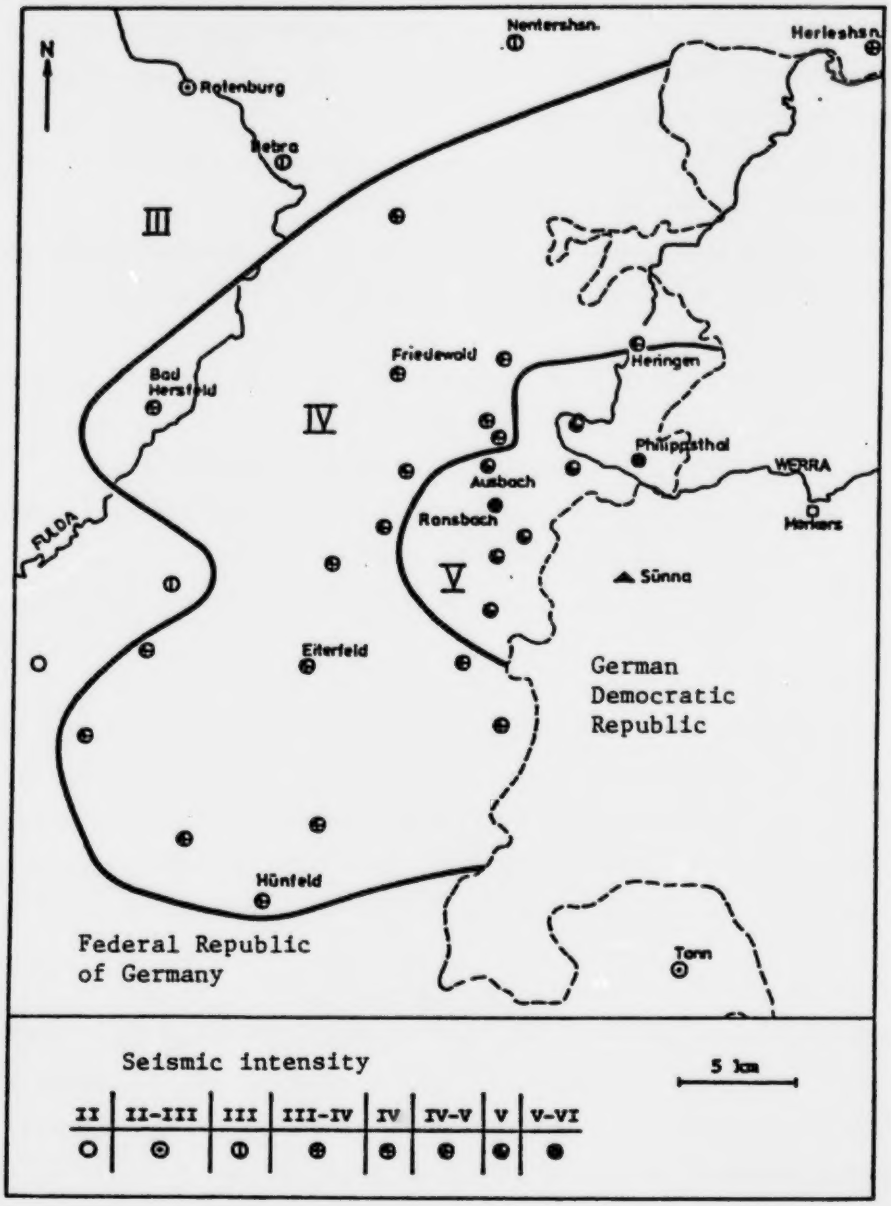


Fig. 2-33: Seismic intensity of the Unterbreizbach rockburst at Sünna, June 23, 1975 (after LEYDECKER, 1976; Abb.1).

by CORNELIUS (1954) after the 1953 rockburst. The writer (l.c., p. 272) notes very little damage to buildings in West Germany.

LEYDECKER (l.c., pp. 276/277) arrives at the conclusion that the sudden settlement by 11 cm of 1 km^2 of overburden could yield the energy of the rockburst. His calculation is based on the assumption of 600 m of overburden above the mine workings. Although this assumption is incorrect, as shown previously, it is a fortunate error because the thickness of the sandstone plate in the rockburst area is 600 m. The salt rocks around the mine workings respond by stress relief creep to any excavation, and such stress relief creep may have allowed some subsidence of the dolomite formation underneath the sandstone plate. The 600 m sandstone formation continued to behave elastically until its tensile failure, the rockburst, took place.

For this reason, the calculation appears acceptable. It remains to be seen if reliable data on the mining situation and on instant surface subsidence are published. Although some writers revised their hypotheses considerably, see 1.2.1.1, the lack of detailed information on the 1975 rockburst makes it impossible to provide better than general interpretations of the mechanism.

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CHAPTER 3

OTHER FAILURES IN CONVENTIONAL MINING

3.1 SO-CALLED ROCKBURSTS, HATTORF POTASH MINE.

3.1.1 Geology and mine development

According to UHLENBECKER (1980), six so-called rockbursts occurred at the Hattorf potash mine between 1967 and 1973. These failures were caused by standard room-and-pillar mining of the lower potash bed in the Werra basin, Germany. The lower potash bed consists mainly of carnallite. In the mined-out upper potash bed, sylvinite pillars provide full overburden support, see I/5.2.5.

The writer reports sudden brittle failure of carnallite pillars near the extraction front. In contrast to others, the writer reports immediate reaction of the overburden to extraction mining; approximately 50% of the measured underground subsidence show at the surface after only a few weeks. Surface subsidence troughs are shown travelling ahead of advancing extraction fronts, indicating considerable abutment loads due to inadequate pillar dimensions.

The problem is evident; the writer ignores stress relief creep. Effects of stress relief creep, such as spalling off pillars and bed separation, are mistaken for effects observed when pillar models are crushed in so-called briquetting experiments, see 2.4.1.4.

The reader is referred to the published map, Fig. 1-1 (UHLENBECKER, 1980), which shows the lease of the Hattorf mine bordering the leases of the Wintershall-Heringen and the Unterbreizbach mines. The scale given in the reference figure (1:25000) is the scale of the original map. The boundary against the Unterbreizbach lease exceeds 7 km in length.

According to the writer, the strongest so-called rockburst at the Hattorf mine occurred in 1969; it affected 36 pillars in an area of 450 x 180 m near the extraction front. 26 of the affected pillars measured 30 x 30 m. The damage due to spalling off the pillars and due to roof failure is reported as particularly severe near the extraction front. The writer attributes the failures to an unexpected increase in thickness of the extracted carnallite from 4 to 6 m; the increase in thickness was not accounted for by a corresponding increase in pillar dimensions.

Due to the 1969 event the pillar dimensions were increased to 45 x 45 m; the room height was limited to the maximum of 7 m; the room width of 15 m was not changed. According to the writer no more rockbursts occurred after these changes were made; however, contradicting himself, the writer also reports rockbursts until 1973.

UHLENBECKER (1980, pp. 12-63) stresses the significance of frequent gas outbursts at the Hattorf mine, reporting spans of 30 - 40 m of outburst cavities (l.c., p. 54). SCHNEIDER (1973) puts particular emphasis on the negative effects of gas outbursts at the Hattorf mine. The writer (l.c., pp. 8/9) evaluates the increase in accidents caused by rock fall; 90% of the accidents occurred near advancing faces; more than 50% of the accidents took place within 24 hours after the advance of a face.

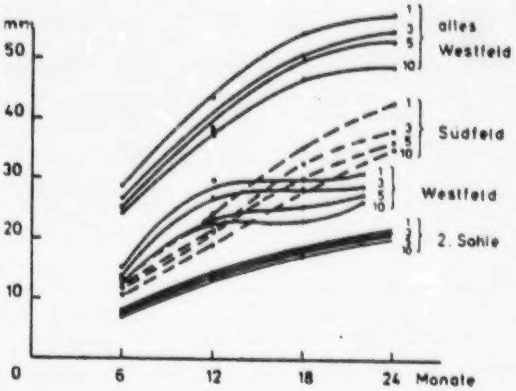
The writer considers his evaluation of accident statistics as definite proof that spalling and roof bed separation do not require long periods of time.

However, the writer apparently is misled by questionable briquetting experiments and other laboratory tests which are considered representative of the in-situ loading conditions of carnallite pillars. Some of his figures are presented and discussed as they reveal serious errors in the interpretation of creep deformation of carnallite pillars shortly after excavation. The total disregard of stress relief creep around mine openings in carnallite appears particularly strange as the writer considers carnallite as "extraordinary mobile" (l.c., p. 33).

The reader is referred to I/2.4.3, particularly to Fig. I/2-21 which explains why layers of carnallite are frequently present above the potash beds in the Werra district; large amounts of CO_2 were occluded in such layers which crystallized in bed separation voids. SCHNEIDER (1973, p. 37) emphasizes the particular capability of carnallite to occlude CO_2. The gas was present at the time of crystallization of carnallite in bed separation voids during the Tertiary volcanism which also fed the basalt zones shown on UHLENBECKER's (1979 mine map, Fig. 1-1.).

3.1.2 Mechanism of the so-called rockbursts

Fig. 3-1 (SCHNEIDER, 1973) shows underground subsidences measured in various mined-out areas with different room and pillar dimensions. The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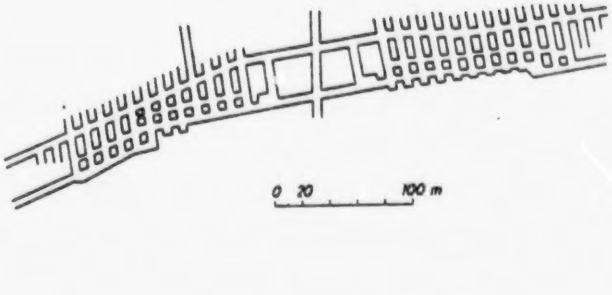
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interpretation cannot be accepted for various reasons given in the following discussion. As a matter of fact, the writer contradicts his own interpretation elsewhere in his publication, attributing underground subsidence mainly to what is called loosening of the roof strata of openings.

Referring to UHLENBECKER (1971), the writer calls for wave-like roof deformation as lateral deformations extend over the outer pillars (l.c., pp. 18/19); the pillar cores are believed to be stable, keeping the overburden in its original position. Reference is made to numerous other German writers (l.c., p. 17) who ignore two most important facts of salt and potash mining at great depths:

(a) stress relief creep cannot be prevented, but can be utilized as practiced in Canadian potash mines;

(b) reloading creep under full overburden load on mine pillars results in considerable underground and surface subsidence, see Chapter 7; final underground subsidence rates are constant, and so are the corresponding surface subsidence rates.

In contrast, the curves of Fig. 3-1 indicate asymptotic final values of underground subsidences as expected by writers who postulate ultimate stability of mine pillars, see I/5.2.5. Underground subsidence due to stress relief creep is missing as the measuring systems were installed much too late. Fig. I/4-5 suggests that at least several centimetres of initial roof subsidence are missing. It is re-emphasized that final constant convergence rates develop at the Hattorf mine according to UHLENBECKER (1971, 1974), see Fig. I/5-5.

The curves of Fig. 3-1 give some clues as to the development of the roof deformations. The roof subsidences were measured at pins anchored near pillars at the indicated depths of 1 - 10 m into the roof.

As deformations were measured only near pillars, but not over the cross-sections of the rooms, most of the roof sagging due to buckling and bed separation does not show in the curves.

For this reason the minimal changes to the distances between the curves of Fig. 3-1 are significant; even minimal changes indicate much more roof sagging at the center of openings where tension fractures may initiate roof failure. In rooms with insufficient widths, shear failure may occur as shown in detail in Chapter I/4.

SCHNEIDER (l.c., p. 54) shows the photograph of a typical shear fracture with starting angles of 20 - 30° against the roof. Similar angles are observed in Canadian potash mines where shearing caused difficulties until stress relief mining methods resolved the problem.

It is emphasized that such shear fractures may develop within hours or a few days, depending on the original stress field in which openings are excavated. If shear fractures intersect bed separation voids or planes of weakness (clay beds), roof failure occurs immediately. In cases where the face is advanced by blasting between shifts, the blasts being set off electrically from the surface because of the danger of gas outbursts, rather large areas may be affected. At Hattorf, gas outbursts may have contributed to roof falls and to spalling off the pillars, see 2.4.1.3.

However, the principal cause of early roof falls appears to be buckling due to rapid stress relief creep. This is indicated by the following observations on the four series of curves shown in Fig. 3-1. (I) The series I of curves was measured in the first room-and-pillar test mining panel in the upper potash bed (sylvinite), see Fig. I/5-7 for measured underground subsidences exceeding 60 mm; there are some doubts as to the time period during which the measurements were taken, see pp. I/202/203. However, the writers agree that there were only four measuring stations in the test panel with the following room and pillar dimensions: pillar length 15 m, room width 11 m, average pillar height 2.5 m (UHLENBECKER, 1968, p. 41).

The curves for the 3-m and the 5-m points are grossly overidealized, apparently for the purpose of showing what is expected. In fact, however, the two points nearly co-incide with the 10-m point at the time of 12 months after mining, indicating that the measured deformations, possibly bed separation, occurred in the 1-5 m roof section. These deformations decreased over the following 6 months, while the deformation of the 5-10 m section increased.

Such shifts of vertical roof deformations are typical of stress relief creep followed by reloading, see I/4.2. The cumulative curves of series I clearly demonstrate that most of the stress relief creep took place above the 10-m point. However, as pointed out before, the measuring systems were set up too late, so the initial rapid stress relief creep is missing.

(II) The series II of curves is supposed to show measured underground subsidence in the first large mined-out room-and-pillar area in the upper potash bed. According to UHLENBECKER (1968, p. 52), the pillar design length is 16 m; the room dimensions are given as 12-14 m, with average heights of 3.5 m. SCHNEIDER (1973) makes no mention of any changes to the design dimensions.

Fig. I/5-7 shows a large, separate underground subsidence trough in the area, the maximum subsidence exceeding 80 mm; the reader is referred to the discussion, pp. I/203/204; the 80-mm underground subsidence trough developed within two years after mining according to UHLENBECKER (1968, 1971). Fig. 3-1 shows only 50% of that value; the contradiction cannot be clarified due to the lack of reliable data.

The increase in the vertical deformation of the 1-3 m roof section of series II is considered significant; the increase began one year after mining, apparently indicating pillar reloading. The cumulative subsidence curves of series II resemble those convergence curves of Fig. I/5-2 which are identified with an R to indicate the beginning of pillar reloading.

The increase in deformation of the 1-3 m section of series II is indicative of buckling due to pillar reloading; this is also indicated by the typical courses of the curves. This conclusion is in agreement with another report (UHLENBECKER, 1968, p. 55) of 50 mm of underground subsidence measured only 1/2 year after the extraction had begun.

The lack of published data covering the following decade appears to confirm that the mined-out area was no longer accessible due to extensive roof falls. However, surface subsidence data should be available; the fact that such data are not published appears to indicate unexpected subsidences.

Fig. I/5-7 shows an extension of the 80-mm underground subsidence trough into an area extracted along the eastern lease boundary against the Unterbreizbach mine. The reader is referred to the discussion in I/5.2.4, pp. 204/205. The published mine maps (SCHNEIDER, 1973; UHLENBECKER, 1980) show considerably increased pillar dimensions; apparently, the first change was to pillar design dimensions of 26 x 26 m with room widths of 16 m (SCHNEIDER, 1973, fig. 34). Three rows of 68-m pillars were left south of a large remnant pillar.

The writers give no reasons for these changes. UHLENBECKER's (1980) map shows basalt zones in the area. It appears that the southward extraction of this area was terminated in 1975 after the Unterbreizbach rockburst, see 2.6.

(III) Roof failure problems and unexpected surface subsidence may be the reasons why the pillar dimensions were changed when the extraction advanced westward from the first mined-out area with 16-m pillars; SCHNEIDER (l.c., p. 58) reports 26-m pillars and 16-m rooms. UHLENBECKER (1980, fig. 3) shows surface subsidence troughs travelling westward with the extraction front, but fails to give quantitative data on measured subsidences. Apparently, basalt zones shown on the mine map halted the westward development.

Again, the two writers contradict each other regarding the underground subsidences; the series III of curves in Fig. 3-1 shows maximum underground subsidences of 30 mm, while Fig. I/5-7 shows another separate trough with underground subsidences in excess of 60 mm. The reader is referred to I/5.2.5, p. 203.

(IV) The series IV curves of Fig. 3-1 show the average underground subsidence at 41 stations in the developing carnallite extraction area in the lower potash bed. The writer's mine map shows most measuring stations located in the initial development area with room and pillar dimensions as tested in series I, with the exception of pillar heights of 4 m instead of 2.5 m. The writer wonders why the average underground subsidences are much smaller in the lower potash bed, although the pillars consist mainly of carnallite; his explanation is that the high deformability of carnallite results in more lateral pillar creep; the wave-like roof deformation observed in the sylvinitic upper potash bed according to UHLENBECKER (1968) is smoothed.

It may be correct that the wave-like roof deformation is reduced due to increased creep of carnallite pillars. However, the writer ignores the fact that the underground subsidences shown in Fig. 3-1 are absolute subsidences measured near the pillars. If carnallite pillars with about twice the height of sylvinite pillars indeed deform easily by creep, the underground subsidences in the lower potash bed should be much higher than those shown in series I. In addition, there should be much more sagging into the rooms due to lateral pillar creep, contrary to what series IV shows; in contrast to series I, hardly any loosening in the first 10 m of the roof strata is indicated, although buckling and bed separation should be considerable.

The series IV of underground subsidence curves shows maximum subsidences of approximately 20 mm, while Fig. I/5-7 (after UHLENBECKER, 1974) shows a separate local trough with maximum subsidences in excess of 60 mm. The reference to the depth of 900 m indicates that the measurements were made in the carnallite extraction area. Apparently, the series IV curves indicate theoretical expectations rather than actual measurement data; the rapid initial stress relief creep is missing. In principle, the series IV curves resemble the series I curves; no reloading of the pillars after rapid stress relief creep is indicated.

According to SCHNEIDER (1973, p. 61), the underground subsidence rates exhibit maximum values immediately after the excavation of rooms; the subsidence rates generally decrease more or less quickly, but regularly, as shown by the series IV curves. Such decrease is typical of convergence due to stress relief creep; as stated at the beginning of 3.1, most German writers believe in laboratory testing and ignore stress relief creep. This causes most of the contradictions in publications which deal with the mechanism of underground subsidence and roof failure. SCHNEIDER (1973) and UHLENBECKER (1968-1974) refer extensively to East German writers who consider spalling off pillars as indicative of pillar failure; in fact, such spalling indicates safe pillar behavior as emphasized repeatedly.

3.1.3 Dangerous extraction sequence

The reasons why a separate subsidence trough developed quickly above the carnallite extraction area in the lower potash bed are apparent: the extraction began immediately at the shaft safety pillar with the radius of only 200 m at the depth of approximately 900 m.

In an area approximately 1 km long, with the maximum span of less than 600 m, the room and pillar dimensions tested in mining the sylvinitic upper potash bed were used, although the average pillar height increased from 2.5 m to 4 m.

Apparently, the small span between the shaft safety pillar and virgin ground prevented full reloading of the stress-relieved carnallite pillars during the initial extraction phase; as pointed out above, this is also indicated by the series IV curves of Fig. 3-1.

Stress relief creep and lack of pillar reloading means that abutment loads build up around mined-out areas. Abutment loads result in corresponding increases in the initial stress relief creep rates and frequently cause roof failure problems; the intensity of gas outbursts also is increased as the gas pressure corresponds to abutment loads.

The changes to the pillar dimensions apparently reflect reactions to difficulties resulting from abutment loads. The first change to pillar dimensions of 26 m was insufficient; in 1969, after the so-called heavy rockburst reported by UHLENBECKER (1980), the dimensions were changed to 45 m.

The last increase improved the w/h ratio of pillars with the height of 6 m to 7.5. In the first extracted area with pillar heights of 4 m, the w/h ratios are only 4.

The writers provide no explanation for the first design with w/h ratios of 4. UHLENBECKER (1968, 1971) repeatedly postulates the minimum w/h ratio of 6 for carnallite pillars; the writer refers to DREYER (1964, 1967), GIMM and PFORR (1961), HÖFER (1958), HÖFER et al. (1967), and others who consider brittle failure of carnallite pillars as rockbursts.

Possibly, DREYER's (1960) postulate to make carnallite pillars small for better creep, see 2.5.3, led to the choice of the pillar dimensions adopted in the first design with the w/h ratio of only 4.

UHLENBECKER (1980) claims that correct pillar design prevented the collapse of a large mined-out area, or even the collapse of the whole mine. Such apparent exaggerations should not be taken seriously as the writer wants to justify his extensive laboratory experiments on model pillars.

The lack of reliable in-situ measurement data makes it difficult to provide an interpretation of the mechanism of the so-called rockbursts at the Hattorf mine. Instant subsidences and surface fractures as observed on occasion of so-called true rockbursts are not reported; if this is correct, tensile failure of the sandstone formation above the mine workings did not take place. In addition, the upper potash bed was already extracted above the carnallite mining area. Previous extraction resulted in reported long-term surface subsidence rates of 3 - 5 mm/year. Large remnant pillars were not left unextracted in the upper potash bed

(UHLENBECKER, 1980, fig. 2); the writer emphasizes basalt zones intersecting the potash beds in N-S directions at distances from 600 to 1200 m.

The writer calls for "additional loading of pillars due to the extraction"; additional loading is defined as loading in excess of the deadweight of the overburden according to depth and extraction ratio. Under "special conditions," the additional loads are believed to have a "dynamic" effect, whatever that is supposed to mean; apparently, the writer is using the terminology introduced by KVAPIL and PFORR (1960, 1961), see 2.4.1. "Dynamic loading" is postulated to take place particularly near an advancing face, and in cases where remnant pillars are undermined. It is shown in 2.4.1.2 that such postulates make no sense in cases where the "normal" pillars support the full overburden load.

UHLENBECKER (1980) also stresses the "dangerous reaction by brittle failure" of carnallite in cases of sudden changes to the loading conditions, ignoring the proven fact that stress relief creep zones travel ahead of slowly advancing faces; the erroneous interpretation of his Figures 4 and 5 is discussed in I/5.2.5.

If indeed the rockbursts at Hattorf represent failure of carnallite pillars, serious damage to the Ransbach shaft is inevitable for the following reasons.

According to UHLENBECKER (1968, pp. 14/15), the concentrated extraction of the carnallitic lower potash bed near the shaft safety pillar was still in the initial phase in 1968. The writer emphasizes the extraction ratio of approximately 66%; this means 2.66 m of underground subsidence until the creep deformations cease.

In the case of pillar failure in rockbursts, short-term overburden subsidence must be expected as the main overburden is drawn into the failure area. According to the writer (l.c., p. 41), more than 50% of the measured underground subsidences show at the surface within weeks or months in cases where full support is provided by pillars. Apparently, the subsidence of the main overburden is not delayed by plate-like behavior of the sandstone formation. Accordingly, short-term overburden subsidence must be expected if the pillars in a mined-out area are destroyed in rockbursts, as postulated by UHLENBECKER (1980).

Angles of draw of 30° to 35° were determined above the Hattorf mine (UHLENBECKER, 1968, p. 53). When these angles are used to construct the intersection of the plane of draw with the Ransbach shaft, one finds that approximately 280 to 350 m of the shaft above the lower potash bed are not affected by draw into the failure area. When these values are applied to the section provided by UHLENBECKER (1980, fig. 1), one finds the plane of draw intersecting the Ransbach shaft near the dolomite formation into which waste brines are disposed. The upper part of the shaft is drawn into the subsidence trough.

Considering the underground subsidence of 2.66 m which must be expected in the case of pillar failure, one can only hope that the pillars near the shaft safety pillar were not destroyed in rockbursts; otherwise, damage to the shaft at sensitive depths and waste brine inflow into the mine most certainly would have occurred.

3.2 OVERBURDEN COLLAPSE, STASSFURT ANTICLINE

3.2.1 Historical and geological background

Many hundred publications deal with the history of potash mining at Stassfurt, Germany. According to LÖFFLER (1962, pp. 154 ff.), salt production from natural springs at Stassfurt can be traced back to the 12th century. The presence of potash was detected in 1843. However, the first two shafts sunk at Stassfurt in 1851 were supposed to mine rock salt rather than potash.

The first attempt to mine potash was made in 1858; it failed because of gases. The first mined potash arrived at the surface in 1861.

A total of 31 shafts were completed at both flanks of the Stassfurt anticline; 19 of them were lost to flooding. Three more shafts were abandoned at shallow depths because of heavy water inflow in the gypsum caprock. In 1962, 4 of the remaining shafts produced rock salt; only the two shafts of the Neustassfurt mine, see 2.2.5, were still used for potash mining.

For nearly the entire 19th century, potash mining was restricted to the Stassfurt anticline because it was the only known potash deposit. Hundreds of publications are dealing with the disastrous learning period in German potash mining; no attempt can be made here to report in detail on all the mistakes which caused the loss to groundwater inflow of 19 out of 31 completed shafts.

Readers who do not read German are referred to WEAVER (1963) for a general outline of the history and the geological conditions of the early potash industry.

Most German writers, e.g., GIMM (1968), tend to blame the disastrous development of potash mining at Stassfurt at the lack of experience in mining under the given geological conditions. This may hold true for the civil servants who administered the state-owned first potash mines. However, extensive experience was available from salt mining under similar conditions over many centuries, for example in Romania where rocksalt has been mined for millenniums. German inexperience in this type of mining should not be used as an excuse; little use of common sense would have prevented the collapses and mine floodings at Stassfurt, and the resulting surface damage. The reader is referred to 2.2 with respect to earthquakes caused by potash mining.

The following general description of the geological conditions encountered in the Stassfurt anticline is based on data published by LÖFFLER (1962); these reports are given preference over those found in textbooks (GIMM, 1968; DREYER, 1974a). Numerous shortcomings and errors in these textbooks indicate that the students/assistants who wrote various chapters are biased by preconceived hypotheses and lack of familiarity with geological situations which must be considered carefully in matters as complex as the mechanics of mine collapses and floodings.

Some of the geological features encountered in the Stassfurt anticline are shown in Figs. I/2-27 to I/2-29. The anticline is much wider at Stassfurt than at locations only a few kilometres to the NW where the anticline resembles an elongated diapir; little of the 500-m Zechstein 2 rocksalt is present near the top of the diapiric structures.

This structural difference must be considered in any interpretation of the collapses and floodings as already recognized in early publications referred to by LÖFFLER (1962, p. 157): at Stassfurt, the anticline is a normal anticline of the "Stassfurt-type," see Fig. I/2-28. With increasing distance to the NW, the so-called "Asse-type" develops; it is described as "a narrow zone resembling a tectonic fracture into which the salt was squeezed; the overburden was not pierced."

While the 500-m Zechstein 2 rocksalt is partly dissolved at Stassfurt, it is not affected in "Asse-type" structures because it did not come close enough to the surface.

It may be mentioned that both West and East Germany are operating atomic waste disposal facilities in "Asse-type" diapirs; the long-term deformations due to creep into the repositories are bound to result in difficulties similar to those experienced in mining in "Asse-type" structures.

The two case histories presented in the following are representative of the Stassfurt-type and the Asse-type structures, respectively. The general geology according to LÖFFLER (1962) is outlined as follows.

Some facts reported in I/3.6.2 are re-emphasized: the salt rocks of the Stassfurt anticline and fracture systems in anhydrite members of the Zechstein evaporites may contain gases. Numerous gas occurrences immediately underneath the present top of the salt provide definite proof of the impermeability of salt rocks under approximately 300 m of overburden.

Depressions along both sides of the anticline contain thick lignite deposits. These deposits date the main phase of salt movement into the anticlinal structures. However, the surface morphology is inverted by solutioning at the top of the anticline.

The carnallite of the Stassfurt potash bed was converted into kainite where groundwater gained access through the residues of salt dissolution (caprock) as shown in Fig. I/2-29. Thus the kainite may be considered as the caprock of the Stassfurt potash bed. Kainite was used as a fertilizer without being upgraded in refineries; it was mined extensively during the first decades of potash mining in the Stassfurt anticline.

Mining of the kainite caprock immediately underneath the solution residues caused most of the floodings of potash mines in the Stassfurt anticline and in other anticlines with comparable geological conditions.

Referring to LOTZE (1938), LÖFFLER (1962, pp. 176-178) shows the top of the salt at depths from 25 to 150 m below MSL all along the Stassfurt anticline; the same contour map can also be found in LOTZE (1957, fig. 219). At several listed locations, gypsum is present in outcrops at the surface which are intersected by rivers.

The writer emphasizes apparent relationships between the depths to the top of the salt near the flanks of the anticline, and the depths of carnallite conversion to kainite: the deeper below surface the top of the salt is found near the flank, the more kainite is present. The depths to the top of the salt near the flanks are listed as ranging from 160 to 250 m below surface.

LÖFFLER (1962, pp. 178-182) provides detailed statistics on the development of the inflow rates in various mines.

The interested reader is referred to the reference publication. Data regarding the two case histories are presented in the respective following sub-sections. Similar data can be found in statistics re-published by GIMM (1968, pp. 432-437).

The latter writer fails to provide statistics on the numerous gas occurrences in the Stassfurt anticline. The writer (l.c., p. 547) reports explosive gases encountered in 1856 when the first shaft sank through the potash bed; in 1860, gases were again encountered when exploratory entries were driven; soon thereafter, gases were encountered at other mines of the Stassfurt area. The writer appears unaware of the significance of these gas occurrences, mentioning only two more occurrences in 1907 and 1910, respectively (l.c., p. 552).

It is re-emphasized that the numerous gas occurrences immediately underneath the caprock of the Stassfurt anticline are the most significant clue in any interpretation of the mechanics of the mine floodings. These gas occurrences show beyond doubt that the salt rocks became permeable due to the mining activities.

Statistics on gas occurences in potash mines in the Stassfurt anticline can be found in publications (LÖFFLER, 1962; GROPP, 1918). The writers provide data on the locations in the respective mines, on the composition of the gases, and on the duration of the individual gas flows into the mines. One case drew the following remark (LÖFFLER, l.c., p. 183): heavy gas outflows (in 1905 in the Leopoldshall IV mine) burned for 4 years with a flame several metres high.

Gas outflows which could be pinpointed were ignited to prevent accumulations of gases, as had been customary for many centuries in other salt mining areas.

TABLE 3 - I

Average surface subsidence in the city of Stassfurt (LÖFFLER, 1962)

Time period	Total subsidence (mm)	Average subsidence rate (mm/year)
1883 - 1899	430	25
1900 - 1909	2400	240
1910 - 1919	1300	133
1920 - 1929	330	33

Accumulative subsidence 4,490 mm in 46 years, approximately 100 mm/year

3.2.2 Mine floodings and surface collapse

Details of the two case histories dealt with in the following two sub-sections are not included in this sub-section. For reasons given above this report is mainly based on an unbiased publication (LÖFFLER, 1962).

The writer (l.c., pp. 181-193) emphasizes maximum surface subsidences of 7 - 8 m in the central area of the city of Stassfurt. Subsidence data for several periods of time are compiled in Table 3-I.

Differential local subsidence caused considerable damage to buildings; GIMM (1968, pp. 458 - 464) fails to mention surface damage. However, the writer (l.c., p. 449) claims that the expensive German experience at Stassfurt was utilized when potash mines began operating in other countries. The reader is referred to 2.1.1.

The writer (l.c., p. 449) claims that unnecessary secrecy caused additional floodings in the Stassfurt district; several mines could have been saved if the experience made by others had been utilized. Mistakes were covered up, and misleading data were published.

GIMM (l.c., p. 463) considers the continuous pumping of brines out of the mines as the cause of surface damage. Inadequate pillar strengths are mentioned; however, the writer approves of counter-measures introduced in 1884 (l.c., p. 461): the pillar width was increased from 5 to 6 m; the room width of 10 - 12 m was reduced accordingly, and the rooms were backfilled; in addition, barrier pillars 32 m wide were left between panels consisting of 10 rooms. These design principles have not changed over almost a century, and some theoreticians still promote these potentially dangerous principles.

The writer's explanation of the surface subsidences is presented in literal translation as follows.

The continuous pumping of salt solutions out of 3 mines resulted in groundwater movement in the overburden. Salt solutioning and related surface damage continuously increased. Apparently, large amounts of groundwater were set in motion. The shape of surface depressions in Stassfurt clearly demonstrates that large parts of the depressions are not located immediately above collapsed mine workings; they were caused by solutioning at the top of the salt along the flanks of the anticline. A large flow system formed above the salt, leading to the location of the first brine inflow into the Leopoldshall mine. Fresh water was flowing continuously along the top of the salt where it caused large cavities and related surface subsidences. Fresh water also was flowing through the fractured Main Anhydrite, dissolving carnallite and rocksalt out of its fractures.

In view of published data, such rather vague statements should not appear in a textbook for university students. The reason why detailed data are not mentioned is indicated in the subsequent reference to the Friedrichshall I/II mine which was left to flooding in 1950 (l.c., p. 464).

According to the writer (l.c., p. 463), the flooding of this mine was considered unavoidable when the inflow rate reached 1.2 m^3/min; the inflow started in 1934. The writer assumes that the inflow was caused by leaving too small a barrier pillar between extraction panels at the first level and the second level; excessive bending of the strata is believed to have resulted in fracturing. In the next sentence, the writer theorizes that pre-existing fractures in the roof strata opened and gave fresh water access to the potash bed. The rooms were partially filled with refinery waste; the fresh water is assumed to have dissolved carnallite in fractures of the roof anhydrite.

It is acknowledged that the writer dissociates himself from hypotheses of stress arches and elastic rocksalt plates held until 1960, see 2.7. As emphasized repeatedly in this text, tensile stresses develop in anhydrite beds near the edge of mined-out panels which are separated by large barrier pillars or so-called safety pillars; for these reasons, the panel-and-pillar design adopted during the second half of the 19th century at Stassfurt indeed resulted in opening of pre-existing fractures in the roof strata of the potash mines at Stassfurt.

GIMM (l.c., pp. 463/464) reports in some detail on attempts to intercept water at the Friedrichshall mine before carnallite was dissolved out of fractures in the roof strata. The writer stresses that the "typical gypsum water" of the first inflow was intercepted while the inflow rate was still small. However, subsequent inflows at other locations and at increasing depths could not be intercepted.

The first roof collapses occurred in 1945. In 1950, when the inflow rate reached 1.2 m^3/min, the pumping of brines out of the mine was discontinued for the following reasons:

(1) It appeared impossible to save the mine from eventual flooding as further increases in inflow rates were to be expected.

(2) Continued pumping was assumed to result in salt dissolution and related surface damage as observed when the mines at the opposite flank of the anticline were lost. Less surface damage was hoped for if the mine was left to flooding.

(3) In the first place, it was expected that the adjacent Ludwig II mine could be saved; the inflowing water was diverted to deeper mine levels so it could dissolve carnallite prior to rising to higher levels.

The writer does not bother with the physics of lifting heavy solutions of carnallite from lower to higher levels while the fresh water is assumed to continue flowing downward; the well-known fact that fresh water forms a blanket above heavier salt solutions, particularly in the case of restricted circulation in flooded mine workings, is ignored.

The decision to leave the mine to flooding is declared as successful; within 3 years, the mine workings filled with salt solutions. No inflows into the adjacent Ludwig II mine were detected. The width of the safety pillar is given as 164 m at the depth of 280 m, and as 170 m at the depth of 355 m.

The following results of surface subsidence measurements above the Friedrichshall mine are reported (l.c., p. 464): in 1952, two years after the pumping was halted, a subsidence trough with the maximum depth of 1.05 m formed "within a few days" above the location of the first groundwater inflow; in 1968, the maximum subsidence reached 1.8 m.

The writer considers solutioning at the top of the salt as the cause of the measured surface subsidences.

This statement is stressed again (l.c., p. 465) with reference to assumed groundwater flow channels at the top of the salt. The writer (l.c., pp. 465-468) theorizes that the safety pillars at the opposite flank of the anticline, leaving distances of 28-130 m between the various mines, suffered rock-mechanical damage; for this reason, these safety pillars could not withstand the "hydromechanical forces", whatever that term may mean; even safety pillars with widths of 150 m were penetrated.

In contrast, the safety pillar between the Friedrichshall mine and the Ludwig II mine, although only 164-170 wide, could not be penetrated, in spite of subterranean water flow and postulated extensive salt solutioning at the top of the salt, and in spite of extensive mining of kainite at Ludwig II immediately below the gypsum caprock.

Reversing previous statements regarding groundwater flow channels on both flanks of the anticline, the writer (l.c., p. 466) finally arrives at the statement that salt solutioning along flow channels did not occur above the Friedrichshall mine; this makes the given explanation of surface subsidences inconclusive. The depth of the second mine level is given as 385 m instead of 355 m as reported above.

Such errors, confused statements, and contradictions cannot create confidence in hypotheses which are also contradicted by LÖFFLER (1962, p. 179) who gives the following account of inflows into the Friedrichshall I/II mine:

1934 Inflow rate 3 l/min, increasing slightly in 1935. A 1936 analysis of the brine at the second level is presented; apparently, the sample was taken after the inflow had been intercepted; differences in the $MgCl_2$ contents are emphasized.

1941 Inflow rate 30 l/min; comprehensive attempts were made to stop the inflow, but no details are reported.

1945 Inflow rate 89-90 l/min.

1947 Inflow rate 165 l/min.

1948 Attempts to limit the inflow rate ceased.

1949 Inflow rate 1200 l/min; pumping ceased, mine left to flooding.

There are more minor discrepancies in the statistics presented by the two writers.

This writer suspects that the comprehensive attempts to stop the inflow in 1941 included grouting at excessive pressures which is equivalent to hydrofacing. With reference to Fig. I/4-18, the frequent application of excessive grouting pressures is re-emphasized. The use of water instead of $MgCl_2$ solutions may have accelerated the dissolution of carnallite out of fracture systems since 1941.

The effects of tension zones above the edges of large pillars and the effects of excess grouting pressures are similar; frequently, the result is an unexpected increase in inflow rates.

GIMM (1968) fails to present any information on surface subsidence which may have occurred prior to the one-metre-settlement in 1953; the dimensions of the subsidence trough which reached the maximum depth of 1.8 m within the following 5 years are not indicated. It appears possible that the surface subsidence was delayed by plate-like behavior of the Main Anhydrite as outlined in 2.2.1 with respect to the 1901 rockburst above the adjacent Ludwig II mine. Excessive tension due to deflection of the roof strata, or weakening due to dissolution of salt out of fractures may have initiated the sudden settlement above the Friedrichshall mine. Earth tremors as observed on occasion of rockbursts in the Halle-Stassfurt districts are not reported.

WEAVER's (1963) summary of the historical development of potash mining in the Stassfurt anticline is quoted as it provides another clue for the reasons of some floodings: "As shown by the history of the potash industry's growth in Germany since 1862, disaster to individual mines was caused by their location in geological settings where they were not in the low-cost class. Disaster several times overtook the whole German industry because increased total mine capacity was created without considering the lag in increase of demand in the logical trade territory."

The potash mines in the Stassfurt anticline were definitely not in the low-cost class after they were forced to mine low-grade carnallite instead of kainite; at the beginning of the 20th century, the development of other potash mining districts made the Stassfurt mines a financial burden to the respective companies; leaving a mine to flooding appears to be the easiest way of getting rid of such a burden.

The secrecy surrounding some of the floodings appears indicative of little interest in maintaining surplus mines at considerable maintenance costs. Before and during World War II, the use of most potash mines in the Stassfurt anticline for military purposes provided temporary relief. The reported abandonment of the Friedrichshall mine is one example of how to rid a state-owned industry of a useless mine.

3.2.3 Leopoldshall I/II, Stassfurt

Fig. 3-2 shows the plan of "the first potash mining panel of the world" (GIMM, 1968, fig. 6/5) as typical of the layout of the potash mines at Stassfurt. Rooms and pillars are 6 m wide and high. As the true thickness of the Stassfurt potash bed exceeds 30-40 m, several rooms with these dimensions could be extracted above each other, depending on the local dip of the Stassfurt anticline. 6 m of ore were left between panels at different levels.

At Leopoldshall I/II, the dimensions were similar, except for the room height of 13 m (l.c., p. 357). However, the same writer (l.c., p. 461) also reports different dimensions, such as room heights up to 12.5 m, room widths of 10-12 m, pillar widths of 5 m.

The extraction of kainite began at the 230-m level underneath the gypsum caprock. According to GIMM (l.c., p. 461), the first collapses of rooms and pillars occurred in 1879.

The history of collapses and water inflows at Leopoldshall I/II is compiled as follows from statistics and reports (GIMM, 1968; LÖFFLER, 1962); data published by the latter writer are considered more reliable for reasons given previously; these data are identified by underlining the years of the events.

1858-61: Shafts sunk to depths of 400 m; first salt encountered at the depth of 200 m; depth of the first extraction level 230 m.

1878: First water inflow, 1 l/min; fracturing of pillars, small rock-bursts.

1879: Collapse of 20000 m^2 of the mined-out area. Inflow rate increased to 30 l/min.

1881: More pillars collapsed in a mined-out area of 0.2 km^2; rock-bursts caused shocks like earthquakes; a small crater formed at the surface. Inflow increased to 360 l/min.

1882: Large crater formed at the surface. Inflow rate increased to 450 l/min.

1883: Surface crater widened. Inflow rate increased to 500 l/min.

1897: More surface cratering. The crater was partly filled; a river was diverted as color test proved that river water was flowing into the mine. Inflow rate increased to 1.3 m^3/min.

1899: Inflow rate 14 m^3/min.

1899: Large crater formed at the surface. The inflow rate increased to 17 m^3/min. The crater is now used as a lake resort area.

1900: Mine abandoned; adjacent mine abandoned as 1.3 m^3/min entered from the Leopoldshall I/II mine.

1900: More surface subsidence and damage caused by salt solutioning; pumping terminated in April; in June, the water levels in the two shafts reached the elevation of 40 m below surface. A few weeks later, water entered the adjacent mine through the safety pillar which was only 28 - 130 m wide. Within a few months, this inflow increased to 3 m^3/min. No attempts to save the adjacent mine were made in order to prevent surface damage.

1901: Flooding of the adjacent mine Stassfurt completed.

1907: Flooding of the adjacent mine Stassfurt completed.

No further comments appear necessary, except for the remark that apparently one important lesson was learned: in order to prevent excessive surface damage due to salt solutioning by groundwater inflow into a salt or potash mine, large amounts of brines must not be pumped out of the mine unless the water can be intercepted prior to contacting salt rocks.

3.2.4 Westeregeln I/II, Stassfurt district

This mine, also known as the Douglashall I/II mine, is representative of the "Asse-structure". It is located approximately 18 km north-west of Stassfurt; the near-surface diapiric evaporites are encountered in a zone less than 1 km wide. The Zechstein sequences exhibit near-vertical dip.

The diapiric near-surface structure made it possible to sink the mine shafts through competent sandstone, and to gain access to the Stassfurt potash bed at various levels. None of the 3 mines with 6 shafts northwest of the town of Egeln survived the extensive extraction of kainite immediately underneath the gypsum caprock.

The "Asse-structure" is typical of numerous other anticlines as shown in Fig. I/2-31; the use of the term "salt stock" should not be misunderstood. Most German geologists refer to elongated diapiric structures as anticlines.

LÖFFLER (1962, p. 187) reports true thicknesses of 13-40 m of the kainite caprock of the Stassfurt potash bed at the Westeregeln I/II mine. The height of the excavated rooms was up to 30 m. Kainite mining began in 1886 in a field in which kainite had been explored over the striking length of 1240 m. The writer emphasizes numerous gas occurrences (CH_4 and H_2S). In the area of shaft I the carnallite was not converted into kainite because of the presence of a thick clay cover.

However, at another location, a depression filled with Tertiary sediments and brecciated gypsum was encountered below the 208-m level of the mine. Apparently, the top of the salt was dry in this area of previous salt solutioning. The water inflow which flooded the mine within 10 days accurred in a kainite room at the depth of only 129 m.

In view of conflicting data found in the reference publications, the procedure adopted in the preceding sub-section is used in the following record of events: reliable data (LÖFFLER, 1962) are identified by underlining the respective years.

1871-1873: Shaft II sunk to the depth of 313 m.

1871-1873: Shaft II sunk to the depth of 271 (282) m; the writer is not sure of the correct depth as data from different sources differ; for this reason one value is put in brackets. In 1877-78 (1880), the shaft was deepened to 313 m.

1891: Mine flooded within 10 days when a kainite room collapsed at the depth of 264 m.

1891: Mine flooded within 10 days as water rushed into a kainite room at the depth of 129 m. For several months the water wells at the town of Egeln fell dry. Surface subsidences forced a railway to shut down for some time.

1939: Sudden formation of a crater -- diameter 50 m, depth over 100 m -- above the flooded mine. The crater was filled with 10^5 m^3 of earth.

1941: The same crater re-appeared with the diameter of 70 - 80 m.

None of the writers report on the development after 1941. However, ECKART (1972, p. 621) shows a photograph of the lake which formed above the flooded mine, and provides the following account of surface caving:

The depth at which the water inrush of 1891 occurred is given as 125 m. In 1907, the first sinkhole formed above the location of the water inrush. More cratering occurred until 1964. The photograph shows the situation in 1970.

The writer provides no further details on the dimensions of the lake which appears to cover the entire mined-out area, following the strike of the diapir over hundreds of metres. Apparently, various craters which started out to form individually according to other reference publications now form a rather large depression which resembles a canyon with slopes of approximately 45°.

This writer assumes that groundwater continued to remove salt solutions from the flooded mine workings, the groundwater following channelways in the gypsum caprock along the top of the diapiric structure.

The reader is reminded of the fact that kainite was extracted at depths of only 125-129 m below the surface, while caprock gypsum was encountered at depths exceeding 200 m; therefore, continuous flow of groundwater through the partly collapsed mine workings appears most likely.

ECKART (l.c., p. 621) theorizes that the flooding of salt mines causes considerable surface damage as the inflowing water dissolves salt; the case of the flooded Westeregeln I/II mine is presented as proof. It is re-emphasized that the opposite may hold true; salt solutions in a flooded mine support approximately one-half of the deadweight of the overburden.

The writer's hypothesis is applicable only to cases where the salt solutions are continuously removed from the flooded mine, either by pumping or by groundwater flow; in the case under discussion, the latter apparently took place.

Flooded salt and potash mines at great depths suffer hardly any damage from solutioning if the solutions are not removed. This was demonstrated, for example, at the Cominco potash mine near Saskatoon (PRUGGER, 1978, 1980).

Another thesis promoted by ECKART (l.c., p. 621) is equally unacceptable; the writer postulates that surface fractures above a salt or potash mine cannot occur prior to the flooding of the mine, but may be delayed for decades. Again, the opposite holds true: as shown in Chapter 2, numerous rockbursts above potash mines in Germany caused extensive surface fractures, but no water inflows into the respective mines.

The data presented in Chapter 2 also disprove the writer's statement (l.c., pp. 623/624) that the flooding of carnallite mines caused the strongest tremors ever observed in mining districts, the intensities reaching those of strong earthquakes. The writer refers to GIMM (1968) in presenting the following new hypothesis on the cause of sudden failure of carnallite pillars by splintering: the change to the loading conditions, which is considered prerequisite for splintering failure according to hypotheses discussed in 2.1.1, is postulated to be caused by dissolution of pillar material in flooded carnallite mines.

This postulate lacks common sense; in the first place, the strongest earthquakes caused by German potash mining occurred above conventional dry mines which resumed operation after more or less extended repair periods; carnallite deforms easily by creep and cannot store the energy suddenly released in rockbursts.

Secondly, the amount of carnallite that can be dissolved in stagnant water is minimal in comparison with the amount available in pillars. The writer apparently is not familiar with the solution equilibria of potash salts, ignoring the need for continuing removal of the saturated solutions from the surface of mine pillars; this prerequisite is met only in exceptional cases such as the one discussed here -- and, of course, in cases where saturated salt solutions generated by inflowing fresh water are pumped out of underground mines over extended periods of time, i.e., over many decades as documented in the preceding sub-sections.

3.3 LARGE-SCALE ROOF FAILURES, SCHIERSTEDT POTASH MINE

3.3.1 Correction of misleading publications

The Schierstedt potash mine, located in the Halle/Stassfurt district of East Germany, was abandoned after large-scale roof falls in mined-out panels in 1943 and 1955. In contrast to most other mines in the district, the Schierstedt mine encountered the Stassfurt potash bed in near-horizontal position, see 3.3.2. A mine plan is shown as Fig. 3-3.

The roof falls in individual rooms occurred over extended periods of time, as shown by this writer for the 1943 events (BAAR, 1954a).

The roof falls extended into the shales above the Stassfurt bed, but did not include parts of the overlying Main Anhydrite; they resemble those experienced in numerous other room-and-pillar potash mines were shales form the immediate roof of extracted potash beds. The mechanism is described in I/4.5.3 and I/5.3.2. One case history is shown in Fig. I/5-11; in this particular case some pillars failed because of backfilling with hot refinery waste.

Pillar failures did not occur in the Schierstedt potash mine, neither in 1943 nor in 1955. Published reports of pillar failure are biased by the belief that spalling off the pillar surface indicates pillar failure. In fact, such spalling indicates pillar creep, i.e., safe behavior as emphasized repeatedly.

The authors of Table 2-I fail to give any reason why they include the Schierstedt roof falls in their list of heavy rockbursts; however, the origin of misleading reports can be traced through the publications which deal with these events.

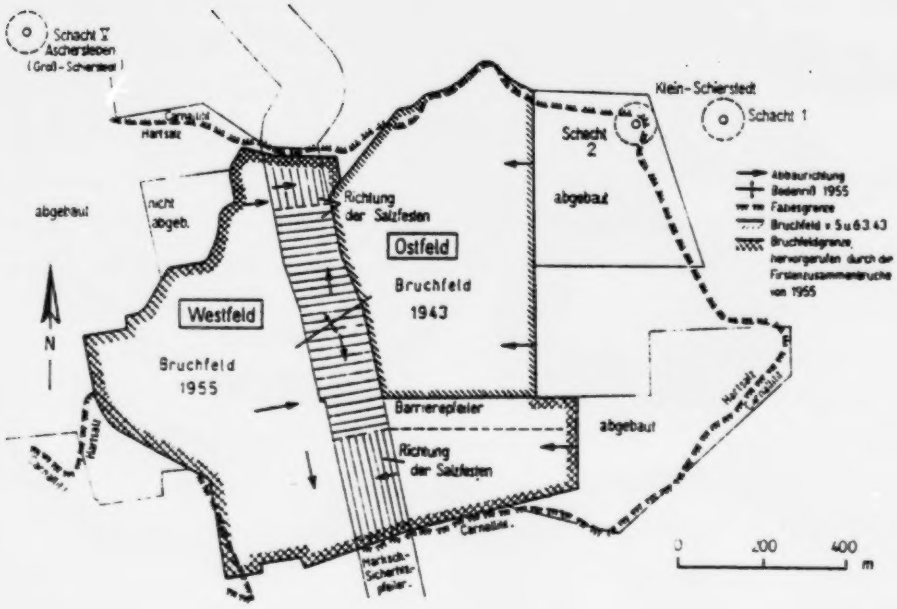
In a detailed account of the 1955 events, JUNGHANS (1956) explicitly states that no pillar failure was observed. The roof falls occurred throughout the second half of 1955.

Regarding the 1943 events, the writer (l.c., p. 491) cites a heavy rockburst as the cause of the collapse of a mined-out area of 0.25 km^2. However, the 1943 roof falls also occurred in individual rooms over an extended period of time. This writer inspected the mine while the 1943 roof failure was in progress. No pillar failure was observed.

During both events, the travelways underneath the floor of the room-and-pillar panels suffered hardly any damage. JUNGHANS (1956, p. 493) stresses that none of the 1943 roof falls reached the bottom of the overlying Main Anhydrite. Proof was not established as the collapsed rooms could not be entered.

GIMM and PFORR (1961) confirm these reports for the 1943 events, but also postulate pillar failure near the centre of the affected area.

Regarding the 1955 events, these writers contradict JUNGHANS (1956), theorizing that large-scale pillar failure occurred in an area of 0.6 km^2.


Schacht V
Aschersleben
(Groß-Schierstedt)
Carnallit
Hartsalz
abgebaut
nicht abgeb.
Richtung der Salzfesten
Ostfeld
Bruchfeld 1943
Westfeld
Bruchfeld 1955
N
Klein-Schierstedt
Schacht 1
Schacht 2
abgebaut
Abbaurichtung
Bodenriß 1955
Faziesgrenze
Bruchfeld v. 5.u.6.3.43
Bruchfeldgrenze, hervorgerufen durch die Firstenzusammenbrüche von 1955
Barrierepfeiler
Richtung der Salzfesten
abgebaut
Hartsalz
Carnallit
Carnallit
Hartsalz-Scheitelpfeiler
0
200
400
m

According to KEGEL (1957), all pillars in the affected areas were destroyed by excessive loads. According to HÖFER (1958c), the pillars failed and yielded to the effect that stable stress arches formed across the mined-out panels. GIMM and PFORR (1961, p. 53) agree with the pillar failure hypotheses, calling for a chain-reaction of pillar failure which started in the centre of the mined-out areas; however, the writers disagree with the hypothesis of large stress arches.

STORCK (1962, p. 349) pinpointed 3 pillars in the centre of the 1943 collapse area where the chain-reaction should have started; according to the DREYER-formula, these 3 pillars - 8 m long, 6 m wide, 7 m high - were loaded in excess of their compressive strength; their failure is assumed to have thrown excessive loads onto neighboring pillars which also failed, and so on, until the chain-reaction halted near the boundary of the mined-out area. The writer (l.c., p. 351) believes that a rock salt plate twice as thick as an anhydrite plate is able to store the same amount of elastic energy; plate-like behavior of the rocksalt above the mine would exclude the formation of large stress arches.

DREYER (1974a) gives the most recent account of alleged facts which are considered causal in both the 1943 and the 1955 "rockbursts." The writer refers to the publications mentioned above, with the exception of STORCK (1962) who interprets the 1943 event on the basis of DREYER's laboratory investigations. This appears to indicate disagreement with the chain-reaction hypothesis.

In general, DREYER's (1974a) account is marred by misinterpretations of reference publications, and by apparent printing errors which escaped correction; for example, it is reported (l.c., p. 110) that a 2-m wide fracture was observed at the surface 3 days after the "main rockburst" in 1955. No such fracture is mentioned in JUNGHANS's (1956) detailed account; GIMM and PFORR (1961, p. 49, and fig. 27) postulate that a surface fracture with the maximum width of 2 cm was caused by the "main rockburst." The location of this fracture is shown by GIMM (1968, fig. 4/84), but the fracture is not even mentioned in the text.

In order to develop a reasonable interpretation of both the 1943 and 1955 events at the Schierstedt potash mine, the geological situation is to be considered in the first place.

3.3.2 Geological situation

LÖFFLER (1962, fig. 36) shows the lenses of sylvinite which were extracted until the Schierstedt mine was abandoned in 1958. The lenses are surrounded by carnallite which was not mined. Some kainite was mined south of shaft V in the Schierstedt anticline. The salt sequences of the Zechstein are considered dissolved by groundwater down to 150 m below MSL. The writer assumes that the solutioning occurred in the geological past; evidence for his interpretation includes the following facts:

(1) Numerous gas and/or brine occurrences were observed after roof falls; the inflow rates decreased in time as shown in Figs. I/4-17 through I/4-20 for similar cases observed in other mines with similar geological conditions. One case history is supported by the following data (l.c., p. 116): at the beginning of October, 1954, a roof fall resulted in brine inflow at the initial rate of 40 l/min; over the following months, the inflow rate decreased to 12-14 l/min; later, the inflow ceased completely.

Numerous other brine inflows at various locations also terminated after various periods of time; they are considered as proof of preexisting fracture systems in the so-called Main Anhydrite above the Stassfurt potash bed.

(2) Numerous gas occurrences at locations throughout the mine show conclusively that the fracture systems in blocks of the Main Anhydrite were neither interconnected over large areas nor connected to the gypsum caprock between shaft V and mined-out areas.

Some of the gas occurrences are listed by GROPP (1918); over a considerable period of time in 1912, gases with 93% H_2 drained out of a borehole into the roof of the C-entry near shaft V; LÖFFLER (1962, p. 116) appears to refer to the same occurrence.

(3) Direct proof of the existence of individual blocks of Main Anhydrite separated by salt squeezed into the gap between such blocks, is presented by LÖFFLER (1962, fig. 60). Such investigations are dealt with in some detail in I/2.4. At Schierstedt, the geological conditions are similar to those found in other mines which extract the Stassfurt potash bed (BAAR, 1954a, b, with numerous examples). This writer concluded that overburden subsidence should be initiated in order to avoid sudden slippage of anhydrite blocks when mined-out areas reach spans which no longer prevent the bending of fractured roof formations.

Two important facts emerge: the Main Anhydrite above the Schierstedt mine was fractured; rockbursts because of its plate-like behavior can be excluded. Secondly, roof falls occurred quite frequently; undoubtedly, extensive roof falls had already taken place in mined-out areas prior to the alleged collapses in 1943 and 1955, respectively.

It should be borne in mind that the travelways were excavated 3 - 10 m underneath the floor of the extraction panels. There was no reason for entering mined-out panels as spalling off the pillars was in progress, and made it dangerous to enter old mined-out rooms. As a matter of fact, it was strictly forbidden to enter abandoned mined-out areas because of possible gas accumulations due to roof falls.

This is the reason why JUNGHANS (1956, pp. 490/491) concentrates on gas observations in the travelways rather than on the question of whether or not pillars in mined-out panels failed. Gases released by roof falls were pushed into the travelways and forced the evacuation of the mine on August 28, 1955.

The mine was not re-entered until September 20, 1955. At that time, roof falls were still in progress, and mined-out panels were not inspected. When the roof falls stopped at the end of 1955, no attempt was made to determine exactly the boundaries of the mined-out areas in which roof falls had occurred.

In other words: the boundaries of collapsed areas shown in Fig. 3-3 are assumed; JUNGHANS (1956) explicitly states that mined-out areas could not be inspected.

Consequently, the question of whether or not pillar failure occurred in so-called collapsed areas cannot be answered on the basis of observations; it is a matter of opinion.

Some of the published opinions completely disregard the geological conditions; the Main Anhydrite was severely fractured and must not be considered as an elastic plate.

Fractured Main Anhydrite exhibits pseudo-plastic behavior when overburden subsidence takes place; sudden slippage of individual blocks may result in minor shocks, particularly at the beginning of overburden subsidence. With progressing subsidence, the developing tension causes fractures to widen, so the probability of sudden slippage of anhydrite blocks is reduced.

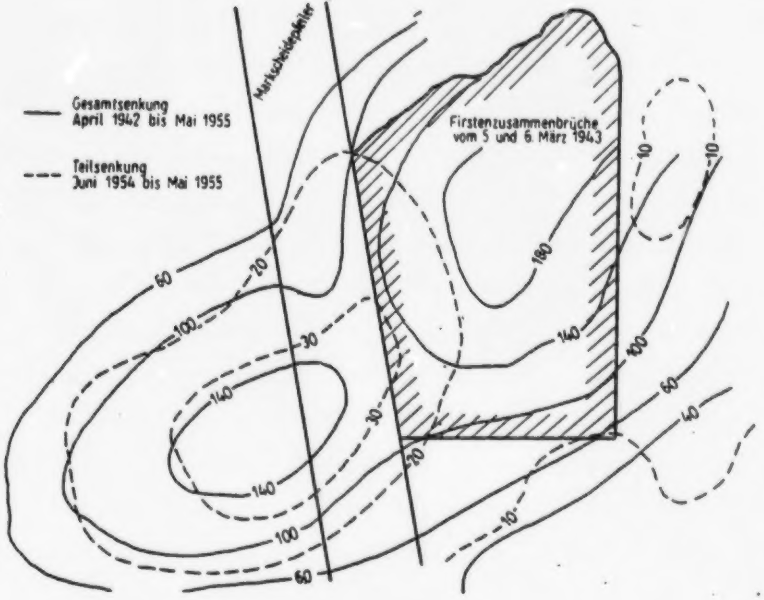

Gesamtsenkung
April 1942 bis Mai 1955
Teilsenkung
Juni 1954 bis Mai 1955
Markscheidepfeiler
Firstenzusammenbrüche
vom 5 und 6. März 1943
10
10
180
140
100
60
40
20
30
60
100
30
140
140
30
20
100
60
10

Table 3 - II

Schierstedt potash mine. Room and pillar dimensions (GIMM and PFORR, 1961). Theoretical average pillar loads (KEGEL, 1957).

Area and year of roof failures	Rooms		Pillars	Theor. pillar load
	Height (m)	Width (m)	Width (m)	(kp/cm^2)
East field, 1943	7	10	6	288
West field, 1955	5	9	7	247
Safety pillar, 1955	7*	10	6**	263

* 5 m according to DREYER (1974a, p. 109)

** 7 m according to KEGEL (1957, p. 486), 8 m according to JUNGHANS (1956, p. 492)

Needless to say that sudden slippage of anhydrite blocks may result in sudden additional load on mine pillars; existing spalls may be ejected. Shock waves generated in this way or by roof falls in individual rooms can be picked up by suitable instruments.

The minor shocks reported on occasion of both the 1943 and the 1955 events are satisfactorily explained in this way. However, the increases in subsidence rates remain to be interpreted.

3.3.3 Mine development

The two mines which became the Schierstedt potash mine in 1948 were separated for many decades. The West field of Fig. 3-3 was mined from 1896 to approximately 1931. Later it was used for military purposes; in all probability, special rooms were excavated as was the case in most potash mines taken over by the military. One example of serious consequences of such special excavations in rocksalt underneath mined-out potash panels is dealt with in I/4.6.4.

In 1948, the West field was connected to the East field for the extraction of some remnants of sylvinite and of the separating safety pillar. The pillar was approximately 150 m wide and 800 m long (not

500 m, as erroneously reported by GIMM (1968, p. 239).

Different room and pillar dimensions were used in the formerly separate mines, and for the extraction of the safety pillar; the dimensions are listed in Table 3-II.

Reasons why the rooms were 5 m high in the West field and 7 m in the East field are not given in any of the reference publications. It appears safe to assume that, in the West field, 2 more metres of salt rocks were left against the roof shales for better protection against roof falls. These 2 additional metres of roof salt in combination with the reduced pillar height make an important difference; the 1943 roof falls in the East field did not extend across the safety pillar into the West field.

The mined-out area near shaft V was carefully backfilled to prevent groundwater inflow. KEGEL (1957, p. 486) stresses that the owners of the West field were cautious in their mining methods because they had lost several other mines to flooding.

Considering the causes of the 1943 events in the East field, KEGEL (1957, pp. 485/486) doubts that the pillars were indeed 6 m wide as designed; he emphasizes that the pillars were overloaded, exhibiting strong indications of "fatigue." As outlined in I/3.4.1, this means that the pillars deformed continuously by creep.

The effects of spalling are shown in I/5.3.1. Such effects were to be expected in the East field when its span reached the depth below surface, approximately 500 m. In 1943, the span of the mined-out area along the safety pillar against the West field came close to 500 m.

Considering the known effects of stress relief creep, one is safe in assuming that spalling had reduced the actual pillar widths to 50%, or even less, of the design width of 6 m. In this case, the theoretical average pillar loads listed in Table 3-II would have been twice as high, possibly higher, if corresponding surface subsidence had occurred to reload the pillars after initial stress relief creep.

However, surface subsidence of any significance is not reported until 1943. This means that the pillars in the collapse area were not loaded according to depth and extraction ratio. Stress relief creep is to be considered as the main cause of the spalling off the pillars reported by all writers.

3.3.4 Correction of published subsidence maps

The surface subsidence maps (JUNGHANS, 1956, GIMM and PFORR, 1961) show hardly any surface subsidence until 1943.

After the 1943 roof failures in the East field, the surface subsidence above the East field and the West field developed only minimal differences, as is clearly demonstrated by the surface subsidence contours shown in Fig. 3-4. Two separate troughs of surface subsidence developed, one above the East field over 180 mm deep, one above the West field over 140 mm deep. The difference in depths reflects the differences in the pillar dimensions and in the spans of the mined-out areas.

It makes no sense to postulate entirely different mechanisms of subsidence control for the East field and for the West field until September 1955.

The contours of Fig. 3-5 indicate continuing subsidence control above the whole mined-out area, i.e., control by pillar creep as shown in Chapter 7 for cases where the writers do not anticipate pillar failure.

3.3.5 Mechanism of the roof failures

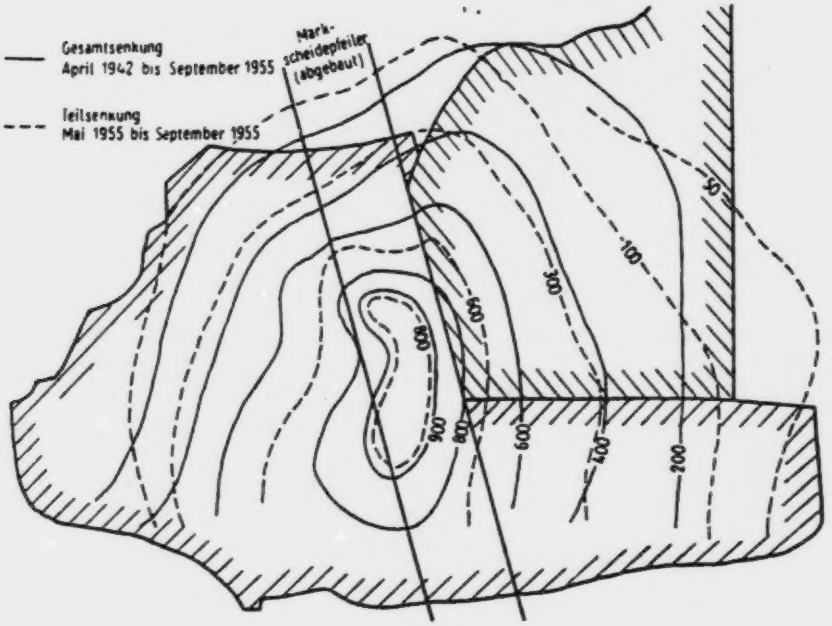
The published information is sufficient to interpret the mechanism of the roof failures in 1943 and 1955 as follows:

(1) The 1943 roof failures had no influence on the behavior of the sandstone formation above the evaporites, as evidenced by the surface subsidence contours of Fig. 3-4.

The bending of fractured anhydrite results in tensile stress which widens existing fractures; slippage of anhydrite blocks may cause light shocks, so-called small rockbursts, as observed frequently at numerous other potash mines under comparable conditions (BAAR, 1954a).

The overlying rocksalt reacts by creep deformation to all changes in loading conditions as evidenced by the lack of any water inflow from the sandstone formation.

(2) Fig. 3-4 shows two separate surface subsidence troughs with maximum subsidences exceeding 180 and 140 mm, respectively. Subsidence of the main overburden was delayed above both the East and the West fields until the extraction of the safety pillar resulted in larger spans of the mined-out area.


Gesamtsenkung
April 1942 bis September 1955
Teilsenkung
Mai 1955 bis September 1955
Mark-
scheidepfeiler
(abgebaut)
50
100
300
600
800
900
800
600
400
200

(3) The extraction sequence of the safety pillar is criticized extensively by most writers (particularly GIMM and PFORR, 1961; GIMM 1968). The writers postulate the extraction of the safety pillar should have started in its center; in this way, the "rockburst" could have been prevented. The surface subsidence data show this hypothesis incorrect. The postulated extraction sequence would have caused large-scale roof collapses much earlier for the following reasons.

Apparently, the span of mined-out areas is the critical parameter for the initiation of subsidence.

In 1943, the critical span for the initiation of subsidence of the Main Anhydrite was exceeded in the East field. However, the sandstone formation continued to behave like an elastic plate as shown by the surface subsidence data. Apparently, the span of the sandstone formation remained subcritical until 1955 because of the extraction sequence of the safety pillar; the remnants of the safety pillar continued providing abutments for the sandstone plate.

Considerable abutment loads were accumulated on the last remnants extracted early in 1955; however, Fig. 3-4 shows that the critical span of the sandstone formation was not reached until May 1955.

The critical span would have been reached much earlier had the extraction of the safety pillar begun in its center. Widening the 1943 collapse area by mining the safety pillar as postulated would have caused much earlier overburden subsidence.

(4) The subsidence contour lines of Fig. 3-5 show the beginning of uniform subsidence during the 1955 events. None of the writers who republished the original figure bothered with correcting apparent errors in drawing the contour lines.

According to the subsidence characteristics (Fig. 7-1), the 600-mm contour lines must be shown closed within the boundaries of the mined-out area; on the original map, this is shown at the northern boundary, but not at the southern boundary.

Closure of the 300-mm contour line should be shown above the southern boundary of the mined-out area, as is the case at the northern boundary. Corresponding corrections were required for the 100-mm and the 50-mm contour lines.

It is unconceivable that no more surface subsidence occurred after

April, 1956 as postulated in various publications. Apparently the student who prepared the original drawings erred, and the error escaped correction in subsequent publications. If pillars with heights of 6 - 10 m (after roof failure) are totally destroyed in a large mined-out area, as postulated by most writers, much more than 90 cm of surface subsidence must take place. Apparently, the overburden subsidence is still controlled by pillar creep; pillar failure did not take place.

3.4 LOCAL ROOF FAILURES IN SALT AND POTASH MINES

Roof failures in individual entries and rooms are dealt with in some detail in Chapters I/4 and I/5. Frequently, rapid stress relief creep causes either shear failure or buckling failure, or a combination of both types of failure. The problem is particularly serious in overlapping abutment zones in deep mines; stress relief mining methods developed in Canadian potash mines resolved these difficulties.

Local abnormal geological conditions may still pose problems even if stress relief mining methods are used; it is necessary that those in charge at the face fully understand the phenomenon of stress relief creep. If abnormal geological conditions are encountered, immediate reductions in opening widths may be required to prevent roof failure. On the other hand, the need for certain minimum opening widths to prevent shear failure of salt roofs is re-emphasized.

Needless to say that roof failure problems caused by creep are aggravated in cases where pillars are reloaded due to overburden subsidence. It may be necessary to protect entry systems for long-term service against reloading; the protecting pillars on both sides of an entry system must have the width of the abutment zones, as shown in Chapter 7. However, in cases where the overburden tends to exhibit elastic behavior which may result in rockbursts, it is necessary to control the subsidence carefully by adequate pillar dimensioning; it may be advantageous to have long-term service entries underneath the mined-out area instead of protecting them by large pillars.

3.5 UNCONTROLLED FLOOR DEFORMATIONS

3.5.1 Outline of problems

Vertical convergence due to continuing creep poses the principal problem in entry systems in deep salt mines. In homogeneous salt deposits, roof and floor deformations may contribute equally to undesired closure of mine openings. In flat-lying, stratified deposits, floor deformations frequently cause most of the closure. Excessive floor heave must be prevented because certain minimum heights of roadways must be maintained for sufficient clearance when the huge machinery used in modern mining operations is relocated.

Economic considerations provide another reason why floor deformations are undesirable: it is advantageous to maintain a smooth floor; frequently, roadways and workshops are paved, and repair costs may become excessive if floor uplift is not prevented.

Stress relief methods prevent excessive floor deformations in mine openings for long-term service. The theoretical principles behind these methods are outlined in detail in Chapters I/4 and I/5.

The objective of the following section is to show why and when excessive floor deformations must be prevented underneath extraction panels, and how this can be achieved. Under certain geological conditions, lateral creep out of the abutment zones of mined-out areas causes large-scale floor deformations which may be extremely dangerous.

Disastrous consequences of large-scale floor deformations in German potash mines are re-emphasized as they involved "the loss of many lives and mines," see Chapter I/1.

One important prerequisite for adequate control of large-scale floor deformations is the initiation of overburden subsidence, see Chapter 7. Surface subsidence measurements should be made to find out if there is any delay in overburden subsidence.

Particular potential danger of excessive floor deformations is caused by gas, oil and/or brine. These fluids may be present underneath an extracted salt or potash bed, or migrate into stress-relieved areas underneath developing extraction panels.

The discharge of fluids from isolated reservoirs underneath salt and potash mines is dealt with in section I/4.6. With reference to

Figs. I/4-17 through I/4-21 it is re-emphasized that the release of gases from such reservoirs is particularly dangerous as pressurized gases expand when entering mine workings.

A relatively simple, though expensive method of preventing the untimely release of gases from such reservoirs is to drain the gases off through long boreholes ahead of mining; at least one case history of successful application of this method is known from a number of publications, and dealt with in the following sub-section.

It follows from the relationships discussed in section I/4.6 that brine outflows from isolated reservoirs, in which the gas pressure is the driving force, can be controlled by reducing the gas pressure.

Another serious problem in controlling floor deformations may arise from solutioning processes in conventional room-and-pillar mines; the pillars may be weakened by fresh water, or by brines which are not saturated with respect to highly soluble potash minerals. Case histories are presented in Chapter 4.

Temperature increase due to backfilling with hot refinery waste has similar effects, as emphasized in I/3.7.

One common aspect of dangerous floor deformations is their principal cause, the insufficient restraint against large-scale creep of saltrocks out of abutment zones.

The migration of pressurized fluids into separating roof and/or floor strata increases the effects of other causes of excessive roof and floor deformations. It has been known for decades that such negative effects of fluid pressure can be controlled safely by drilling holes into developing bed separation voids; the migrating fluids can be drained off continuously, see I/4.5.2 and I/4.6.

Such solutions to difficulties arising from migrating fluids must not be attempted in cases where brine reservoirs have hydraulic connections to groundwater aquifers; in such cases, fresh water or nonsaturated brines replace the brines which are released into the mine. These relationships, and the danger involved in applying too much pressure in grouting operations near mine openings, are dealt with in detail in Chapter 4.

The migration of highly pressurized fluids into mines proved particularly dangerous in the South Harz potash mining district of

Germany. Some case histories are presented as similar geological conditions may be encountered in other salt or potash mines.

3.5.2 South Harz district, Germany

3.5.2.1 Geological and historical background

Typical geological profiles of the strata underneath and above potash mines in the South Harz district of Germany are shown in Figs. I/2-16, I/2-19, and I/5-13A. The latter figure also shows schematically the creep deformations which are initiated in developing room-and-pillar extraction panels; the development of bed separation voids underneath mined-out areas is documented by WILKENING (1958).

Fig. 3-6 shows a schematic section through a potash extraction panel; it is based on observations in and around panels where oil, gases, and/or brines were forced out of a cavernous dolomite formation underneath the potash mines in that district.

Apparently, the thickness of the rocksalt sequence between the dolomite and mine-workings is the most important factor to be considered in designing extraction methods in this mining district. The rocksalt sequence provides an impermeable seal against the reservoirs underneath the mines; however, its thickness is only 30-40 m near the western boundary of the East German part of the district; the thickness is increasing gradually to 80-100 m at the eastern boundary, and to more than 500 m in the main Zechstein basin (see Fig. I/2-6 for regular bromine profiles of the rocksalt sequence).

The South Harz potash mining district developed since the beginning of this century. The quality of the Stassfurt potash bed is excellent in areas where the original carnallite was converted locally into high-grade sylvinite as shown in Fig. I/2-16. Due to this origin, the sylvinite areas are of limited extent; some mines soon had difficulties in finding high-grade sylvinite; they were abandoned or kept in stand-by condition, see WEAVER (1963) for a summary of the early development.

For various reasons outlined by BAAR (1960), most of the potash mines operating in the South Harz district were in difficulties at the beginning of the 1950's; the known sylvinite reserves were nearly exhausted, partly because of manpower shortage during and after World War II.

Lack of underground exploration and misdirection of exploration efforts due to misleading geological hypotheses were the main reasons.

Readers interested in details are referred to published maps (BAAR, 1960; GIMM, 1968). For unknown reasons, several potash mines are not shown on the latter map. The misleading geological hypotheses (RICHTER-BERNBURG, 1966, pp. 614-618) postulate primary facies differentiations in the Zechstein basin and its sub-basins, including the South Harz basin, to the effect that sylvinite would be found only near the boundaries of the basins. These hypotheses are shown erroneous by the actual distribution of high-grade sylvinite in the South Harz district as shown on the maps referred to above.

The maps show local transitions from carnallite to sylvinite and barren zones; in most cases, such alterations are clearly attributable to post-depositional processes as shown schematically in Fig. I/2-16; "gases, if present, are occluded only in what BORCHERT and MUIR (1964) termed 'reaction minerals,'" see I/2.2.3.

There are however, other areas in which the conversion of the highly soluble carnallite into sylvinite occurred immediately after the deposition of the Stassfurt potash bed, see I/2.1.2.3.

Along the boundary of the sub-basin, groundwater action had similar effects. However, with only one exception, the potash mines kept sufficient distances from areas affected by groundwater solutioning.

The potash distribution map referred to above (BAAR, 1960) was presented in 1952 to support the proposed exploration for sylvinite from existing potash mines; this was considered necessary to avoid the uneconomic extraction of carnallite postulated by several writers. After heated discussions (BAAR, 1953b, p. 10) this writer obtained the assignment to direct the proposed exploration.

The underground exploration proved successful, as shown in detail by STOLLE (in GIMM, 1968, pp. 77-86).

The underground program appeared in jeopardy when some writers postulated changes to mining methods which turned much of the new sylvinite reserves into barrier pillars.

Published controversies during the early 1950's should be viewed against the background outlined in the preceding summary of the development of the South Harz mining district; this writer, on assignment to find sylvinite reserves for the operating mines, had no choice but to show some hypotheses erroneous (BAAR, 1952a, b, 1953 a-c, 1954 a-d, 1955).

3.5.2.2 Unique case: potash mine becomes oil producer

In 1930, oil started flowing out of a developing long-room panel at the Volkenroda mine. The design width of the pillars was 5 m. Similar flows of smaller amounts of oil and/or gas occurred in other isolated mined-out panels of the mine. Governmental mine inspectors, unaware of the dangers posed by explosible gases, set off several explosions when inspecting the panels with open lights.

The composition of the gases - analyses can be found in GIMM (1968, Table 10/1) - clearly indicated the origin of the oil, and of associated gases and brines: the fluids were stored in suitable geological structures of the dolomite formation underneath the Zechstein 2 salt sequence.

Gases of similar composition had been encountered previously in other potash mines of the district. However, the 1930 oil flow in the Volkenroda mine was the event which triggered oil exploration in most existing potash mines; the exploration holes were drilled from the mine workings into the underlying dolomite formation.

At some locations, the anhydrite at the basis of the salt sequence also contained fluids in fracture systems, see Fig. I/2-16. Tectonic events in the geological past allowed the stored fluids to ascend into overlying formations, and finally to the surface. At most locations, the bulk of hydrocarbons disappeared in this way, so the exploration for oil from potash mines proved unsuccessful.

At the Volkenroda mine, which is connected to the adjacent Pöthen mine, the exploration for oil and gas had some success. However, the principal achievement was the removal of oil and gas from structures underneath future potash mining panels. Some statistics (from GIMM, 1968, p. 548) are presented as follows.

At the Volkenroda mine, a total of 242 oil exploration holes were drilled from the potash level at depths exceeding 1000 m. At the Pöthen mine with depths exceeding 1100 m, 40 holes were drilled.

The holes were drilled at angles of approximately 45° to intersect as many fracture systems underneath the rocksalt as possible. 25% of the holes encountered oil and gas, 10% hit brines only, and the rest remained dry. Frequently, the gas was not associated with oil; the reservoirs were occupied by brines under gas caps. The writer emphasizes that the reservoirs are not connected to groundwater aquifers as such connectiors would have allowed the gases to escape.

Obviously, individual reservoirs were not interconnected; the pressure in each reservoir dropped from the original lithostatic pressure to the atmospheric pressure. Apparently, the flow rates were governed by the relationships shown in Fig. I/4-15, and in Figs. I/4-17 through I/4-19.

From 1931 to 1938 a total of 82 000 metric tons of oil were produced. The gases were utilized in the refinery.

In 1951, the potash extraction had reached areas which had not been included in the oil exploration program during the 1930's; gases released from the floor of an isolated developing potash panel were accidentally ignited; the explosion caused numerous fatalities.

3.5.2.3 Duplication of 1930 case history in 1951

The following report is, in part, literally translated from GIMM (1968, p. 552); the writer reports 26 serious gas accidents in potash mines of the South Harz district which claimed 46 lives.

At the Volkenroda mine, the first explosion in 1930 as described in the preceding sub-section claimed 3 lives. Another heavy explosion of gas from floor strata occurred on July 2, 1951, in the interconnected Pöthen mine. The mined-out rooms were not backfilled as a system for hydraulic backfilling was missing. Mined-out areas of considerable extent were left open at depths of approximately 1100 m.

The room in which the explosion was set off was several years old. Heavy floor heave (2 m) had taken place. The gases accumulated over a weekend and were ignited by an electrical spark at the beginning of the Monday morning shift. The explosion claimed 9 lives.

The writer fails to mention the practice of shutting down the ventilation system over weekends, and the fact that an atmospheric low pressure system had just reached the area. It is well known that gases accumulated in unaccessible mined-out areas enter active mine workings under such conditions, so the explosion cannot be blaimed at unusual rock deformations.

The latter also holds true for another methane explosion which occurred 9 days later at another mine in the district. A roof fall pushed gases, which had accumulated in a mined-out panel, into a travel entry where mining crews took their coffee break; the gases were ignited by open light, killing 12 and injuring 22 miners.

The statistics published by GIMM (1968) and other writers do not include gas accidents which occurred while most of the potash mines in the district were used for military purposes before and during World War II. It is not known if such statistics are available; however, this writer's statement at the end of Chapter I/1 includes a number of serious gas accidents investigated from 1944 through 1947.

Being reminded of unpleasant duties when discussing such disasters is certainly not a pleasure - however, no matter how many theoreticians dislike being reminded of potential consequences of the application of erroneous hypotheses, it is this writer's opinion that those responsible for safe underground operations in salt deposits should be aware of potential dangers from migrating gases, and of mining situations which are known to cause the release of gases into mine workings.

More important for designers of salt and potash mines is the knowledge of how such dangers from gas exhalations can be prevented by suitable methods of controlling excessive floor deformations. Intentional roof caving, where suitable and possible, proved most feasible as shown in Chapter 8.

3.5.2.4 Dangerous belief in backfilling for floor control

For many decades, backfilling of extracted room-and-pillar potash panels with refinery waste has been much praised as a method believed to provide effective control of floor deformations. In fact, however, the contrary holds true because of the temperature increase caused by hot refinery waste.

Belief in hydraulic backfilling as suitable method to prevent floor deformations led to several attempts of total extraction of the Stassfurt potash bed under geological conditions which allow the complete backfilling of an extracted slice immediately after each step of excavation. Such methods were used in anticlinal structures, the face advancing towards the crest of the anticline.

One such attempt was made in the Königshall-Hindenburg mine, see Fig. I/5-10 for a cross-section. The attempt failed because of unexpected floor deformations as documented in detail by WILKENING (1958).

The flooding of the mine in 1957 was not caused by the total extraction of the Stassfurt potash bed, but by the backfilling of a room-and-pillar panel with alledgedly stable pillars, see Figs. I/5-11 through I/5-13B.

The total extraction with immediate backfilling after the face advanced resulted in rock-mechanical difficulties which increased with each step of widening the panel. The large-scale deformations were continuously monitored; readers interested in details are referred to the reference publication (WILKENING, 1958).

Floor deformations, with bed separation voids opening and closing, were not of great concern in this particular panel as rocksalt with sufficient thickness was known to be present underneath the panel. Serious problems were caused by roof falls which extended through the roof shales to the bottom of the overlying Main Anhydrite, see Fig. I/2-19 for approximate thicknesses. Creep deformations of salt rocks out of the front abutment of the advancing extraction front are considered to have caused the roof falls. Such creep was enhanced by increased temperatures as the refinery waste was still hot when transported hydraulically through pipelines into the excavations.

The method of extraction made it necessary to backfill the excavated slice completely after each step of extraction; the top of the backfill served as floor during the following step. The refinery waste, consisting mainly of rocksalt and anhydrite, is known to crystallize to a solid rock mass when the transport brines drain off. There were no problems in this regard; the top of the backfill provided the expected smooth floor.

However, too much stress relief creep occurred during each step of excavation. The solidification of the waste may eventually have stopped further creep; however, the stress-relieved floor rocksalt was not recompressed as a thick sandstone formation prevented overburden subsidence.

As a result, considerable abutment loads developed at the extraction front, increasing with each subsequent step of extraction.

Stress relief creep caused heavy spalling. Eventually the roof caved before the excavated slice could be backfilled.

Measurements (WILKENING, 1958) and additional wire-extensometer measurements in boreholes confirmed that the stress-relieved rocksalt in the floor of the panel was not recompressed. Instead , bed separation void which opened while a new slice was cut closed when the opening was backfilled, indicating at least some effect of the backfilling; it was attributed to the increase in creep deformations when the hot refinery waste caused the temperature of the rocks around the opening to increase.

These measurements and observations showed backfilling with refinery waste ineffective in controlling floor deformation. Increase in creep deformation of pillars embedded in hot refinery waste, see Figs. I/5-12 through I/5-13B, resulted in the flooding of the mine in 1957.

These published measurements and observations should caution the reader against publications which continue to praise the positive effects of backfilling with refinery waste (e.g., GIMM 1968, p. 371, DREYER, 1974a, p. 123).

As the increase in temperature causes the deterioration of the supporting capacity of salt pillars, see I/3.7.1, special caution is necessary in the design of atomic waste repositories in salt deposits.

3.6 THE SIGNIFICANCE OF CARBONATE REEFS

Local carbonate accumulations during the initial phase of an evaporation cycle may pose particular problems as the thickness of impermeable rocksalt underneath potash mines is reduced. The geology of such accumulations is dealt with in I/2.1.2.

Carbonate accumulations in the Prairie Evaporite basin caused particular concern as they may reach the level of the first potash bed.

GENDZWILL (1978) arrives at some remarkable revisions of earlier hypotheses (GENZWILL and HAJNAL, 1971), stating that "some of the anomalous features (encountered in potash mines) no doubt are related to hydrologic conditions which affected local areas shortly after deposition of the potash salts, as discussed by BAAR (1974a). Other anomalies are structural in nature and developed long after the salt deposits were buried. The most obvious of these is the regional dip induced by subsequent tilting of the Elk Point (Prairie Evaporite) basin, averaging about 5 m/km (0.005) to the south. Another type of structural anomaly present in the potash mines is a broad depression with steep flanks, thickness as great as 30 m, and up to several kilometres wide. In these features, the potash beds may simply dip down and then rise again to their normal level, but there are local zones of intense chemical or structural disturbance in some parts of the synclinal lows. In this study, it was discovered that these synclinal features are underlain by Winnipegosis mounds."

The writer (l.c., p. 73) explains why the term "mounds" is used for carbonate accumulations which rise from the basis of the Prairie Evaporites and "commonly are referred to as reefs: there is insufficient evidence that they are true reefs." "Some new information about the mounds was derived from seismic surveys, drill holes, and underground mining. The work was carried out near potash mines (Allan Potash Mines and Central Canada Potash) about 50 km southeast of Saskatoon."

Referring to HOLTER (1969), the writer (l.c., p. 74) states that the first potash bed, which is mined in Eastern Saskatchewan, is absent in the studied area. "The total thickness of the potash-rich beds, including halite interbeds, is about 25 m." Showing five well logs, the writer concludes: "The nearly uniform spacing and thickness of the halite and sylvite beds, whether underlain by mounds or not, imply that they must have been deposited rather rapidly and under uniform conditions of water depth, temperature, salinity, and current action - conditions that prevailed over a distance of at least 40 km."

These conclusions are to be discussed in detail as similar geological conditions are likely to have important implications in other evaporite basins.

Underground investigations in the two potash mines referred to revealed at least 2 types of local anomalies attributable to changing depositional conditions (BAAR, 1974a).

One figure (l.c. fig. 18) shows a local depression at Central Canada potash. Another figure (l.c., fig. 19) shows "an abundance of isolated anomalies in another potash mine near Saskatoon." The mine is the Allan Potash mine (APM); at the time of publication, the APM management preferred the reference to "another potash mine".

GENDZWILL (l.c., p. 74) contradicts his own quoted statements regarding uniform conditions "over a distance of at least 40 km" and elaborates as follows on the variable thicknesses: "The variation in thickness of the uppermost sylvite and halite beds (about 5 m) implies that either the top surface of the salt was partly dissolved by groundwater after the second red bed was deposited, or that there was some vertical movement in these sequences during the last phase of potash and halite deposition. The uniform thickness and character of the second red bed as shown by gamma-ray logs indicate that it was deposited on a relatively level surface, that is, the top of the salt was not affected differentially by erosion at the well locations studied" (five locations "over a distance of at least 40 km"!!).

"In spite of the uniform conditions that prevailed during deposition, the Prairie Evaporite potash beds are now at different elevations from place to place, and in some places in the mines the beds are altered chemically or structurally."

These alterations are attributed to "build-ups or mounds (of carbonates)...scattered liberally over the Saskatoon shelf area ...very few have been tested with even one drill hole."

Seismic investigations are interpreted as follows: "In this area of central Saskatchewan, the mound pattern is an irregular patchwork, with individual mounds 1 to 8 km across and 70 to 100 m high. The salt-filled depressions between them tend to be somewhat broader than the mounds so that overall the structures occupy less than half of the area. The region investigated is indicated by WARDLAW and REINSON (1971) and by FULLER and PORTER (1969) as being part of a single carbonate bank which extends at least 50 km. However, information from several drill holds and from new seismic data indicates that the structure is quite different."

"The major difference is that the mounds are complex in detail, with individual mounds much smaller laterally than the other authors indicated, and with full development of the Whitkow salt in the basins between the mounds instead of a continuous carbonate mound. The slopes are much steeper than they indicated, and the tops of mounds are just about level with the middle anhydrite, in general, not projecting any significant distance above the anhydrite."

The writer shows a figure with subsidence over a reef. Another figure shows the proposed model of solutioning. There is no significant difference between the reef extensions shown by the writer and those shown by JONES (1965; see BAAR, 1974a, figs. 12 and 13).

There is, however, a most significant difference in the relative elevations of the top of the reefs compared to what WARDLAW and REINSON (1971) show: these writers show the top of the reefs at the elevation of the first potash bed; such reefs are the targets of oil and gas exploration and yielded huge amounts of gases with H_2S in Alberta. The potential danger in conventional mining operations at or near the top of such reefs needs no further explanation.

At the time of the latter publication this writer worked under a contract with the Saskatchewan Research Council which called for review of the literature on potash mining to safeguard against unadvisable mining methods; this writer had no choice but to show the potential danger from reefs, if such reefs indeed "are projecting a significant distance above the anhydrite."

This was done in a published report (BAAR, 1972c) with reference to numerous related publications and 37 figures and maps.

Considering previous experience under comparable conditions, see the preceding sub-sections for case histories, this writer felt obliged to a frank discussion of the reef situation in the Prairie Evaporites. With reference to mass accidents in German potash mines, the following statement was made (l.c., pp. 37/38; it is emphasized that this writer's report was edited to conform with the requirements for official reports issued by the Saskatchewan Research Council):

"Unfortunately, when something happens that may arouse public interest, some writers tend to catch publicity by papers which may fulfill that purpose. Such papers, however, are very detrimental to science as it is the impossible to discuss in detail all the fantastic ideas thrown on the market by people who know little about potash mining. Unfortunately, however, such publicity finds believers willing to spend quite some money on following up ideas which have long proven incompatible and even dangerous when put to work in potash mines. With reference to available publications, there is no point in elaborating further on this point at this time."

"The point to be made is that experience, expensive in lives and investments in potash mines in other parts of this world, need not be duplicated in Saskatchewan under similar geological conditions created by carbonate accumulation in local reefs."

The concluding statement (l.c., p. 41) is particularly stressed: "It may be stated that the companies affected by possible occurrence of carbonate reefs are fully aware of the situation, and observe adequate precaution."

Extensive geophysical work was done to clarify the reef situation at operating potash mines particularly at the PCS Rocanville (Sylvite) mine. McLAUGHLIN (geologist for the present owners PCS (Potash Corporation of Saskatchewan), written communication, March 20, 1978) confirmed:

"(a) The reefs could possibly extend to the mining level, in which case there would be the potential danger of mining into a reef. If such a reef contained gas, oil, or water, then there would be the problem of possible flooding of the mine, etc".

"(b) The reefs could possibly extend up to near the mining level. The potential danger here would be from gas, oil, and/or water under pressure in the reef, bursting into the mine workings either along a pre-existing zone of weakness or a weakness created by the extraction of the overlying material.

One must, of course, also consider this as a potential danger even if the reefs contain water not under great pressure since it can be assumed that such water could enter the workings by solution, etc."

Referring to seismic surveys carried out in 1964 and 1969, the writer reports possible reef build-up outside the present mining area; detailed seismic reconnaissance surveys are run on one-half mile grids prior to developing an area for production mining.

The most advanced geophysical techniques, including radar techniques as described by UNTERBERGER (1974, 1978), were used to confirm that there are no reefs located under present extraction mining areas.

In view of the controversies at the Fourth Symposium on Salt (PIPER, 1974), the co-operation of the PCS management in clarifying these important matters is acknowledged.

However, the model of salt solutioning above reefs proposed by GENDZWILL (1978) cannot be accepted for the following reasons:

(1) "Nearly uniform thickness of the halite and sylvite beds" in the investigated area is assumed; the actual thicknesses vary considerably as shown by WARDLAW (1968), see Figs. I/2-12 and I/2-13.

Evidence of shallow-water deposition of salt and potash in the Saskatoon area is presented in the comprehensive report referred to above (BAAR, 1972c, figs. 10A - 10E). Photographs of polygonal depositional patterns found 10 feet (3.3 m) above the uppermost potash bed are presented as evidence of exposure shortly after deposition of the potash bed.

It goes without saying that salt and potash deposition discontinued in exposed areas, while it continued in adjacent depressions; this resulted in varying thicknesses of stratigraphic units. Petrographic structures such as shown in Fig. I/2-12 resulted from brine seepage through exposed fresh deposits into adjacent depressions.

(2) GENDZWILL (l.c., pp. 83/84) refers to "dehydration of carnallite" as "another mechanism which is used to explain structural lows in the potash mines." The meaning of the term "dehydration of carnallite" is not explained.

The mineral carnallite cannot be "dehydrated". Under certain known conditions, carnallite disintegrates and sylvite forms. Such conversion of carnallite into sylvite by contacting solutions results in large amounts of solutions which are rich in magnesium chloride. When these solutions are squeezed out of the deposit, the loss in volume amounts to roughly 50%, see Fig. I/2-19. The seepage of such solutions deeper into unconsolidated deposits results in features as shown in Figs. I/2-12 and I/2-13.

Localized seepage of less concentrated brines resulted in local depressions (sinks) as shown in some detail by BAAR (1974a). "An understanding of the underlying physico-chemical principles must be demanded," see I/2.1.1, p. 11.

(3) HOLTER (1969, fig. 8) shows various concepts of reef configurations in the Prairie Evaporite basin of Saskatchewan. The writer favors "the general concepts of JONES" (l.c., p. 17) who definitely excludes the possibility of water flow underneath the Prairie Evaporites after deep burial of the salt deposits.

(4) GENDZWILL (l.c., p. 85) admits that "the source of fresh water and the presence of a sufficient hydraulic gradient to drive groundwater under the evaporite basin remains to be explained. According to KENT (1964), the South-Alberta arch existed as a land area with moderate relief throughout Middle Devonian time. It is conceivable, therefore, that this land area was a source of deep groundwater flow toward the northeast - a situation not unlike that of today where the regional groundwater flow pattern is much the same with fresh water recharge in the uplands of Montana and saline discharge areas along the Paleozoic outcrop area in Western Manitoba, and eastern Saskatchewan."

Such much publicized hypotheses call for danger to potash mining operations, to storage facilities in the Prairie Evaporites, and to surface structures. They are discussed in more detail in 4.3.
It is emphasized that there is no evidence of ongoing salt solutioning deep in the Prairie Evaporite basin.

Realistic assessments of the effects of salt solutioning in the geological past require more facts and less geophantasy. In the first place, writers must be familiar with the physico-chemical processes which caused the geological conditions encountered in the potash mines of the Prairie Evaporite basin.

CHAPTER 4

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CHAPTER 4

NATURAL SOLUTIONING OF SALT DEPOSITS

4.1 GEOLOGICAL AND CLIMATIC CONDITIONS

If any removal of salt from buried salt deposits is considered as salt extraction, natural salt solutioning by groundwater undoubtedly represents the most widespread salt extraction process; it returns salts to the continuing cycle of evaporation of sea water, precipitation and burial of solid salts, dissolution when geological conditions change, and transportation in solutions flowing back to the original reservoir.

In other words: salt deposits of marine origin are only temporarily taken out of the natural cycle. The lifetime of salt deposits, of course, may comprise any length of time from a few hours to hundreds of millions of years, and the foreseeable geological future.

The natural cycle is dealt with in some detail in Chapter I/2. Man's salt mining operations have little effect on the general balance of the natural cycle: the salt content of the oceans has virtually not changed since Precambrian times.

However, man-made salt extraction operations, particularly conventional "dry" mining operations, can be seriously affected in areas where natural dissolution of buried salt deposits is in progress. Such processes are governed by the groundwater regime of any specific area. The groundwater regime should not be disturbed as consequences might be disastrous. Conventional mining operations definitely must not disturb natural salt solutioning processes to the extent that groundwater flows into the mines rather than back to the ocean.

The significance of water inflow into salt and potash mines is outlined in Chapters I/1 and I/2 with emphasis on experience in German potash mining.

BAUMERT (1955) found that, on average, one potash mine shaft was lost every year. This led the writer to the statement: sooner or later, every potash mine is bound to be lost by flooding.

Such statements, of course, are merely excuses for inadequate mining practices. Deformations caused by salt or potash mining can be controlled safely for the projected lifetime of any mine. Under suitable geological conditions, extraction ratios close to 100% of potash beds can be used.

The same holds true for deep rocksalt mines. However, quite often lack of experience results in risky mine designs and in flooding by groundwater.

The flooding potential at any location depends on the permeability of the overburden formations. With reference to I/3.6 it is re-emphasized that salt rocks are impermeable below certain depths, while other evaporites such as anhydrite may be fractured and permeable.

Additional problems are caused by different solubilities. Salt rocks are easily dissolved in flowing groundwater, while the dissolution of other evaporites requires much more time. Even when exposed to flowing groundwater over geological time periods, anhydrite, dolomite, and limestone dissolve relatively slowly, developing karst features as described in numerous geological publications.

It is not the subject of this text to deal in detail with natural solutioning processes; interested readers are referred to the extensive geological literature referred to in Chapter I/2.

One point is stressed here: the term "saline karst" as frequently used in the geological literature suggests that the dissolution of buried salt deposits creates underground karst features. This is a serious misconception as frequently the opposite holds true. Due to the different solubilities mentioned above, karst features are restricted to soluble rocks other than salt rocks. Related surface features such as sink-holes and solution channels formed during the original salt deposition as shown in Figs. I/2-10 and I/2-11.

Equally questionable is the concept of "downwards percolating meteoric waters" producing "a very uniform, more or less horizontal top surface" ("Salzspiegel") on buried salt deposits (BOCHERT and MUIR, 1964, p. 204).

LOTZE (1957, pp. 362-372) emphasizes his disagreement with such hypotheses as they cannot be reconciled with contradicting facts. Nevertheless, misleading concepts are still used in publications and result in further confusion. For example, "Salzspiegel" is incorrectly translated as "salt mirror" from which brines are believed to flow to great depths, making their "own 'karst' formation" at the flank of a salt dome (BLOCH, 1974).

LOTZE, (1957, p. 370) lists the depths below MSL to which groundwater dissolved the salt deposits underneath the North German plains. At 39 locations, the depths range from 10 m above to 260 m below MSL. The surface elevations generally do not exceed 100 m above MSL. The writer stresses the observation that the very top of salt anticlines and salt domes may be relatively horizontal, but is deflected towards the edges of the structures; this phenomenon is attributed to groundwater flow along the edges.

The writer (l.c., p. 366) stresses particularly his disbelief in lateral dissolution of salt domes deep down the flanks, as assumed by unidentified American authors. Such "lateral attack" is extensively discussed in recent publications dealing with the potential utilization of salt domes for atomic waste repositories (e.g., HAMSTRA, 1976, 1977).

It is difficult to reconcile hypotheses of lateral dissolution of rising salt domes with the stress fields which develop when salt is pushed up from great depths. The driving forces are provided by gravity differences between post-salt sediments and the salt itself. Stresses in rising salt masses are necessarily higher than those in surrounding sediments which are pushed apart or up above the existing surface.

The stress field in surrounding consolidated sediments is characterized by stresses which decrease with increasing distances from a rising salt dome. Migration of formation waters towards the rising salt masses appears highly unlikely. However, migration of oil and gas frequently occurred, the hydrocarbons replacing formation waters which migrated in the opposite direction. These relationships appear well established in numerous oil and gas fields near salt domes. The salt masses are providing an impermeable lateral seal to porous on cavernous sedimentary formations.

The stress conditions in and around salt domes may change after the termination of upward movement. Such termination may be due to exhaustion of the salt supply at depth. A state of equilibrium may be reached between the driving forces and the resistance provided by overlying and surrounding rocks. In the latter case, the top of a salt dome may never reach the near-surface region of moving groundwater. For more details, the reader is referred to I/2.5.2 and I/2.5.3.

As outlined in I/2.5.4 with reference to TRUSHEIM (1960), a gravitative equilibrium is not reached when the salt masses "extrude", salt being continuously dissolved from the rising top of a salt dome.

The erosion of overlying formations has similar effects, as shown by LOTZE (1957, pp. 359-372). The writer places particular emphasis on the difference between salt solutioning in arid or semi-arid areas where salt karst features may develop at the surface, and salt removal in humid climates by subrosion (= dissolution) which continuously or intermittently attacks the surface of buried salt bodies.

The erosion of overlying formations may result in reactivation of the upward movement of salt domes. The regression of ice fronts during and after periods of glaciation had equivalent effects. The re-activation of the upward movement of some salt domes could be attributed to inter-glacial periods (LOTZE, 1957; TRUSHEIM, 1960; numerous other writers).

The fine components of salt deposits, particularly clay minerals, are instrumental in protecting the top of salt deposits against further dissolution by groundwater; the increase in volume of anhydrite upon transformation into gypsum represents another important factor, particularly in flat-lying salt sequences with thick anhydrite beds.

With reference to morphological maps of the surface above two Gulf Coast salt domes, LOTZE (1957, pp. 352/353) stresses the apparent continuing rise of two domes in which conventional salt mines are operating; his main argument is based on the assumption of continuing slow dissolution of salt at the top of the domes which represent islands; the maximum surface elevations exceed the present MSL by only 100 ft. - (32 m).

Precise levelling over another island dome could not detect any changes in surface elevations from 1905 to 1918. The writer considers two possible reasons why the continuing rise of the salt dome could not be measured: either dissolution and surface subsidence are compensating each other, or the rise of the dome is too slow and could not be detected by instrumentation available at that time.

This is a third possibility: uplift due to continuing rise of a salt dome could be compensated by surface subsidence due to salt or potash mining in the salt dome.

The surface subsidence data presented and discussed in Chapter 7 demonstrate that overburden subsidences caused by conventional mining or solution mining may have serious effects on natural salt solutioning processes; this is shown in more detail in the following sections.

Natural salt solutioning strongly depends on the geological history of any particular area. Tectonic features such as fracture zones and faults may govern the groundwater regime. The surface morphology also reflects groundwater flow patterns. These relationships are stressed particularly by CLOOS (see the review of his work in IAEG/AIGI Bulletin No. 13, June 1976).

Similarities between geomorphological features and features forming at the surface of salt deposits under groundwater attack are stressed by LOTZE (1957, p. 366) with reference to case histories, e.g., the development of the Cheshire basin of Northern England where excessive brine pumping accelerated the natural solutioning process considerably, see 4.2.

One important physical relationship must be borne in mind when discussing salt solutioning by near-surface water: in order to keep such processes going, the brines which form at water-salt contacts must be removed continuously. Flowing groundwater provides such a mechanism.

The depths listed above for the North-German plains provide one example. Similar depth ranges for flowing groundwater are known to exist underneath most other large plains. In other words: salt solutioning by groundwater is restricted to near-surface salt deposits.

If salt solutioning at great depths is postulated, a reasonable explanation of the process of lifting heavy brines up from the water/salt interface must be given.

The recompaction of solution residue cannot be invoked as it has the opposite effect; limited amounts of brines are squeezed out of the residue whose permeability is reduced. Sooner or later, groundwater flow through the residue is no longer possible. The recompacted residue protects the surface of the underlying salt deposit against further dissolution.

As a matter of fact, dry surfaces of salt deposits which were under groundwater attack during earlier geological time periods have been encountered in conventional salt and potash mines. One case history of particular interest is presented and discussed in the following section.

4.2 DRY CAPROCK, BERNBURG AREA, EAST GERMANY

LOTZE (1957, p. 338 ff.) shows photographs of miniature salt domes extruding above the solutioned surface of the Zechstein 2 rocksalt sequence in the Plömnitz mine; the mine is located approximately 5 km south-east of the city of Bernburg, East Germany.

The writer stresses the observation of numerous similar "small diapirs" which "intruded" into the bottom of the anhydritic solution residue.

Apparently, these miniature diapirs formed after the solutioning process ceased.

This instructive case history of salt solutioning which terminated completely, leaving a dry caprock, is described in more detail by LÖFFLER (1962). The writer shows the same photographs of miniature salt domes at the top of the solutioned surface of the Zechstein 2 rocksalt. The publication is summarized as follows.

Fig. 4-1 shows the boundaries of solutioning by groundwater of the Stassfurt potash bed, near what is called the Bernburg Main Anticline. This anticline like the flanking Peissen syncline extends in the E-W direction.

7 potash shafts were sunk in the area covered by Fig. 4-1 from 1884 to 1914. The depths to the present surface of the Zechstein 2 rocksalt range from 433 to 541 m below the surface, i.e., from 180 to 255 m below MSL.

The N-S section, Fig. 4-2, extends beyond the southern boundary of Fig. 4-1; it shows a former salt dome in which the anhydrite members of the Zechstein are converted to gypsum.

The writer calls for large-scale lateral salt migration out of the synclinal structure into the Bernburg anticline and into the former salt dome, respectively. The original concept is credited to FULDA (1934) who refers to WOLDSTEDT (1924). Apparently, "halokinesis" was conceived much earlier than indicated in recent publications, see Fig. I/2-31.

The exact thickness of the Zechstein 2 rocksalt is established in the Plömnitz 1 shaft, see Fig. 4-1. In 1888/1889 the shaft was sunk 2 m into the anhydrite at the basin of the Zechstein 2 sequence; its

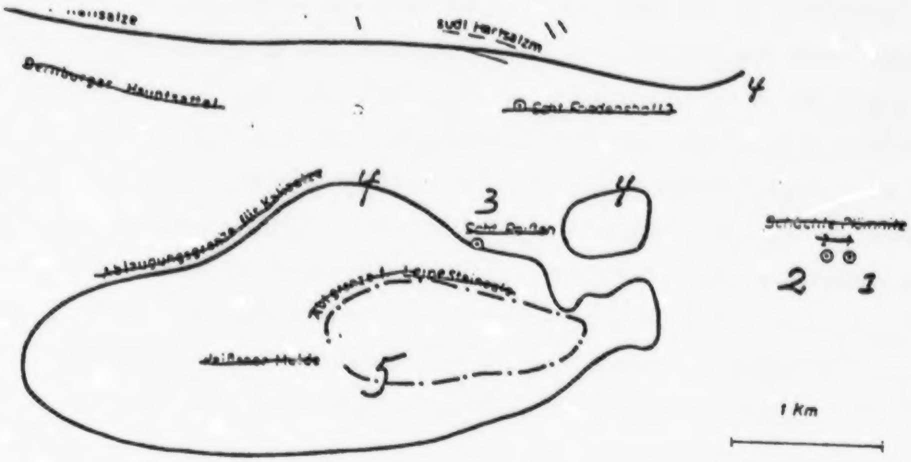

Fig. 4-1: Bernburg anticline and Peissen syncline (after LÖFFLER, 1962)
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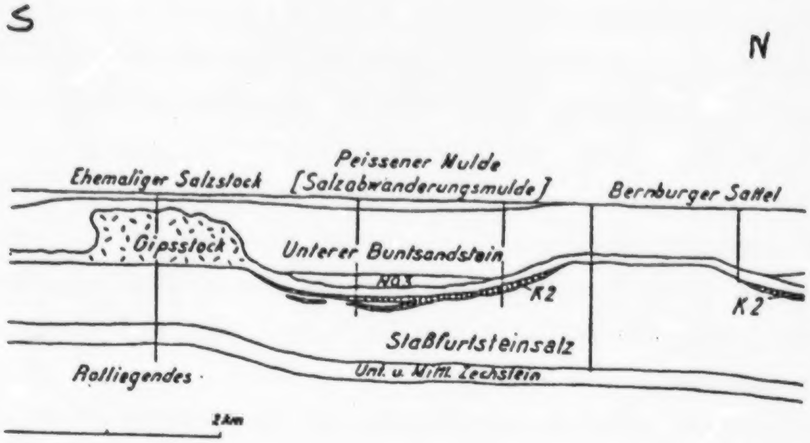

Fig. 4-2: N-S section, Bernburg anticline and Peissen syncline (after LÖFFLER, 1962)

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total depth is 451 m. The thickness of the Zechstein 2 rocksalt is approximately 90 m; the original thickness is listed as 300 - 500 m. The shaft sank through the bottom of the overlying sandstone at the depth of 303 m.

These figures make it possible to calculate the thickness of the solutioning residue (caprock) as approximately 56 m.

Neither the two Plömnitz shafts nor the Peissen shaft encountered the Stassfurt potash bed which had been dissolved by groundwater. The Plömnitz shafts were utilized for underground solution mining of rocksalt in room-and-pillar patterns. The Peissen shaft is listed as abandoned in 1936; the two other shafts apparently are still in operation.

LÖFFLER (1962, pp. 149/150) stresses the fact that none of the 11 potash shafts near Bernburg was lost by flooding; some minor inflows apparently came from isolated fracture systems in the so-called Main Anhydrite, see I/4.6.3 and I/4.6.4 for case histories of comparable inflows. The writer attributes these facts to the recompaction of the solution residues above the mines in the vicinity of Bernburg.

Eocene lignite deposits up to 16 m thick are known at the present surface. Their locations are attributed to surface depression caused by salt solutioning (l.c., p. 135). Apparently, upon recompaction of the solutioning residue (caprock), salt solutioning and related surface subsidences ceased.

Frequent occurrences of gases are reported from all salt and potash mines of the Bernburg district. In 1921, a methane explosion in one mine claimed 15 lives. Another explosion of gases which emanated from the basal anhydrite of the Zechstein 2 sequence at the Plömnitz mine killed 2 miners during the 1920's.

At this point, it is emphasized that gases set free by natural solutioning may provide a brine lifting mechanism; this may allow deeper penetration of groundwater into the top of salt deposits.

On the other hand, the presence of gases near the solutioned surface of the salt deposits at Bernburg provides evidence of recompaction of the solution residue (caprock). Apparently the residue became impermeable and terminated the natural solutioning.

Underground brining operations at the Plömnitz mine provide definite proof of the impermeability of the recompacted caprock. The operations are described as follows (LOFFLER, 1962, p. 151):

From 1884 to 1889, brine was obtained through 4 boreholes from the surface. These boreholes and the cavities created by solutioning became accessible underground when the mine was developed for underground solution mining. Two of the boreholes showed negligible water inflows.

The underground solution mining scheme is characterized by rooms leached at three levels. The rooms of the first level are leached up to the bottom of the caprock.

Room and pillar dimensions are not given in the reference publications. Saturated brine collects on a fourth level. LOFFLER (1962, p. 151) reports some rock mechanical problems such as spalling off entry walls, roof failure, and floor heave.

The same writer (l.c., p. 150) reports surface subsidences exceeding 1.50 m, but stresses that old rooms leached up to the caprock are still accessible; the caprock is dry.

Considering the geological conditions which governed the natural solutioning process, this writer wishes to emphasize the significance of the latter observation. Most of the solutioning is known to have taken place during the Eocene; this is evidenced by thick lignite deposits at the present surface. Apparently, the depth to the top of the salt has not changed significantly since the time of recompaction of the solution residue. The thickness of the overburden is approximately 365 m.

The load of 365 m of overburden apparently recompacted the normal solution residue to complete dryness, as evidenced by the observations discussed above. It appears most unlikely that voids existed at the bottom of the normal residue.

This writer assumes that blocks of the overlying Main Anhydrite settled in such a way that voids remained open, allowing the top salt layers to flow upward into the voids.

The thickness of the overburden allows the calculation of the average overburden load on the solutioned salt surface as approximately 90 kp/cm^2.

Salt apparently closed the small voids completely by creep. This cannot be considered as surprising in view of the known small creep limit of rocksalt.

The miniature diapirs represent another example of the behavior of salt rocks in situ; in contrast to other rocks, salt rocks respond easily by creep to small differential stresses.

4.3 CASE HISTORIES OF LOCAL SALT SOLUTIONING

4.3.1 Grosse Ile, Wyandotte/Detroit, U.S.A.

The case history dealt with in the following discussion occurred hundreds of millions of years ago during the deposition of the Salina formation. The Salina covers large areas of the North-Eastern U.S. from Michigan to Pennsylvania and New York, and of South-Western Ontario, Canada.

Geological maps can be found in numerous publications, e.g., LANDES (1963); PEARSON (1963); BORCHERT and MUIR (1964).

Some mineralogical and petrographic characteristics of the salt sequences of the Salina formation are summarized in I/2.3.1 (after DELLWIG, 1955). MATTHEWS and EGELSON (1954), see I/2.1.2., indicate potash deposition in central areas of the Michigan basin during the first cycle of evaporation of sea water.

The sequence of stratigraphic units, defined A through G (LANDES, 1945), "has become the standard for the Michigan basin and for the subsurface Salina Group everywhere. Surface exposures of the Salina Group are relatively few, poor, and incomplete. Much more has been learned from the study of subsurface well data over the past 20 years than through the efforts of many geologists examining surface exposures during the preceeding 100 years" (RICKARD, 1970, p. 35).

The study of data obtained in a brine field on the Grosse Ile island in the Detroit river unvealed details of localized Silurian salt solutioning. JARON (1970, p. 422) summarizes the results as follows:

"Man-made and natural-occurring collapse breccia, the result of salt cavity roof failure and insoluble ledge collapse, has been investigated at WYANDOTTE CHEMICALS CORPORATION Michigan's underground storage, waste disposal and solution mining operations. Wireline caliper, gamma ray/neutron and sonar logs show the progression of insoluble ledge collapse, debris accumulation on lower insoluble ledges, and the beginnings of cavity filling by rubble during development of an underground LPG storage facility in the B salt of the Michigan Salina."

"A television survey of a hole drilled through the rubble of a mature salt cavity intended for subsurface waste disposal revealed bulking by 'side-walk' size slabs of rubble and very little open hole. Comparison is made with outcrops of breccia found in the Mackinac Straits area which is thought to have a similar mode of origin."

"A solution collapse structure, whose origin is believed to be contemporaneous with the deposition of the B and C units of the Michigan Salina, occupying an area of approximately 40 acres (0.161 km^2) has been investigated. Core samples and wireline logs from wells located in this structure show removal of approximately 200 feet (61 m) of salt from Unit B of the Salina group. Bulking by collapsed insoluble ledges in the B salt section and approximately 50 feet (15.2 m) of overlying Unit C roof rock, plus a thickened undisturbed Unit C dolomitic shale-anhydrite section account for the volume of salt removed. A structure map on top of Unit C shows little or no evidence of the underlying solution collapse feature, thus dating this event."

"It is thought that within reasonable limits, bulking will stabilize a salt cavity and thus serve to protect the overlying section from destructive subsidence. Additional work is required to determine the relationship between salt extraction, cavity bulking, and subsidence. This will serve to define the limits of safe extraction for salt well systems."

Fig. 4-3 (LANDES and PIPER, 1972) shows the normal thicknesses of the Salina units referred to in the foregoing quotation. JARON (1970, Figs. 3-5) demonstrates the localized solutioning of the B salt (Salt 4) by structure maps

(1) on the base of Unit B, "showing little structural relief and a slight northerly dip" (Fig. 4-4),
(2) on the top of Unit B, "showing solution structure" (Fig. 4-5),
(3) on the top of Unit C, "showing little structural relief, dating B salt solution structure as being older than Unit D (Salt 3 of Fig. 4-3).

Figs. 4-4 and 4-5 need no further explanations. The narrow spacing of the boreholes indeed provided convincing evidence of localized

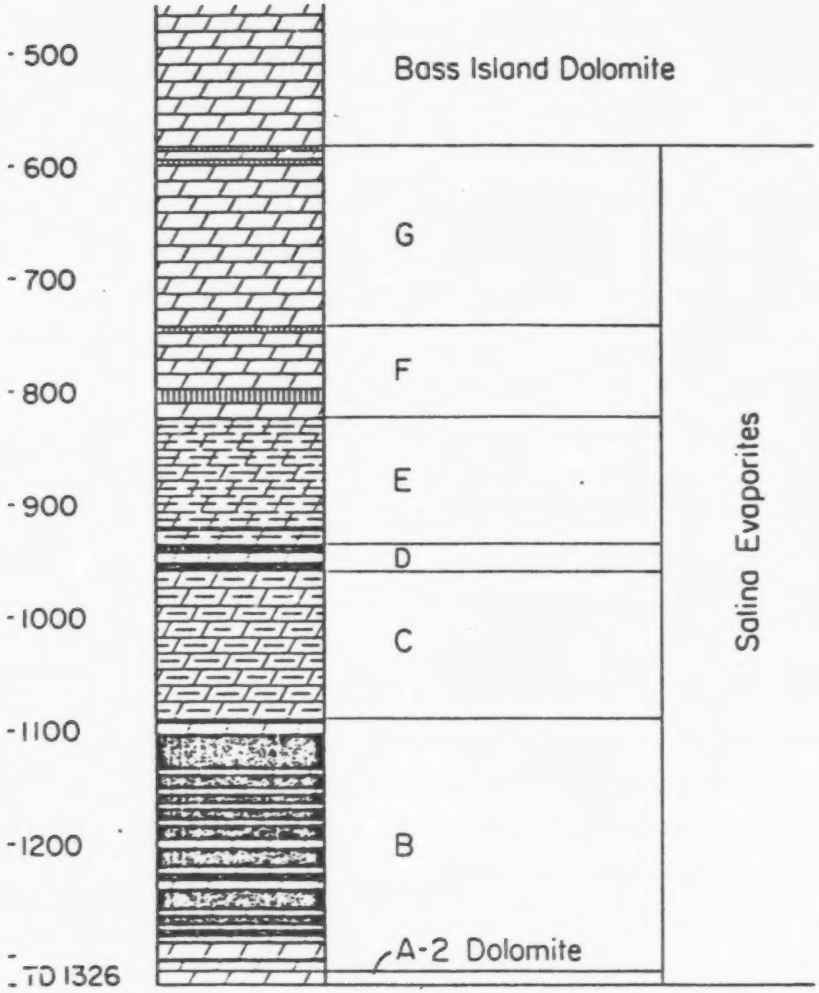


Fig 4-3 Salina Evaporites, Grosse Ile, Detroit (Michigan, in LANDES and PIPER, 1972)

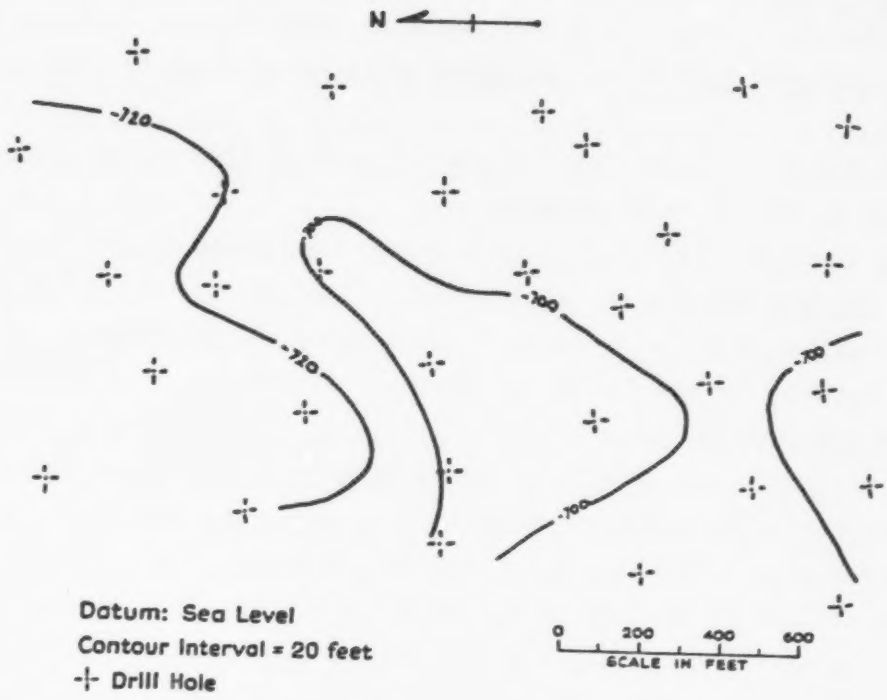


Fig. 4-4 Contour lines on the base of B salt, Grosse Ile (JARON, 1970)

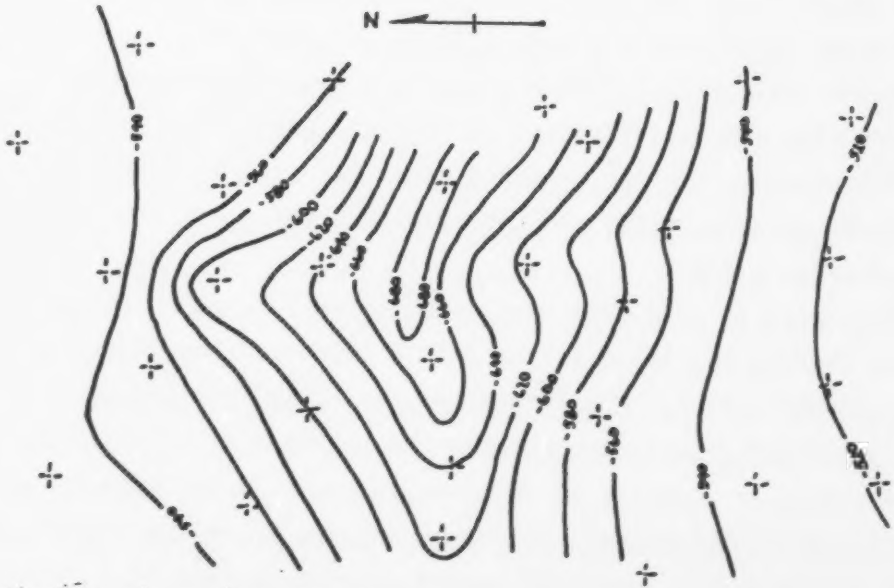


Fig. 4-5 Contour lines on the top of B salt, Grosse Ile (JARON, 1970)

solutioning. Such evidence usually is available only in conventional mining operations in flat-lying salt deposits where similar features were also conserved over hundreds of millions of years as shown by Figs. I/2-10 and I/2-11.

The solution features shown in the two sets of figures are similar in size and in various other aspects.

In this writer's opinion, JARON's quoted comparison of "man-made breccia" with the Silurian solution residue found at Grosse Ile, and with the Mackinac solution collapse breccia described by LANDES (1945) is not acceptable for the following reasons. It appears indicated to quote from JARON (1970, p. 422):

"The occurrence of solution collapse breccia is not an uncommon phenomenon; published observations of this breccia type appear throughout the literature. However, in as much as geologic processes operate within the expanse of geologic time, these reports are for the most part "after-the-fact" reconstructions of the solution collapse brecciation process." The writer continues stating that "in our underground storage, disposal and solution mining operations, we have provided the conditions necessary to create a man-made solution collapse breccia."

Referring to "a series of wireline surveys made in connection with the development of an LPG storage cavity in the B unit", the writer (l.c., p. 423) reports on ledge collapses observed during 4 months of solutioning of 160,000 cubic feet (4530 m^3) of salt out of a cavity from which 440,000 cubic feet (12463 m^3) had been leached previously.

Apparently, the writer refers to problems described by PIPER (1970, p. 470) as follows: "Caving does not cease with the dissolving stage but continues intermittently and unpredictably while the cavity is in use as a storage vessel."

Difficulties of this type were encountered in another solution mining and storage operation in the Salina formation, as described in detail by JACOBY (1970). The interested reader is referred to this publication as the writer demonstrates the possible extent of unpredictable roof caving in a series of sections through a developing brine field.

PIPER (1970) emphasizes: "Storage cavities in salt are usually not developed to the extent that roof caving or stoping sets in - it can be visualized that bulking of the caved material would ultimately occupy all the open space in the cavity if the process were carried to its limit".

JARON (l.c., p. 423) makes a similar statement based on the reported survey: "As more salt is dissolved out, we would expect the cavity to fill with rubble. That this does indeed happen was borne out in a waste disposal project initiated in 1966".

"Two disposal wells were drilled through the Salina Unit B in an attempt to locate large brine-filled cavities. . . Wellsites were located in an abandoned brine field which had been in operation for more than 50 years".

At this point, it is emphasized that the brine field on Grosse Ile, with the Silurian solution structure shown in Figs. 4-4 and 4-5, was in operation from 1943 to 1971. Apparently the disposal wells referred to were drilled in another brine field. JARON (l.c., p. 423) continues as follows:

"However, neither well showed the expected sizeable cavity. Instead, the 200 foot thick Unit B was found to contain only rubble-filled cavity and broken formation. The only sizeable open hole observed was in the 30 foot thick salt-bearing Unit D. Here, two cavities were found separated by a four foot thick dolomite ledge. A television survey was run in an attempt to evaluate the character of the rubble".

The writer shows a picture of the rubble on the cavity floor; "the thick cavings appear to be large angular blocks, resembling slabs of broken sidewalk". The size of the cavity is not indicated.

JARON (1970, p. 423) continues stating that "the angular blocks of cavity debris are similar in appearance and probably too in origin to some of the solution collapse breccia found in Michigan's Mackinac Straits region. Geographically located at the northern end of the Lower Peninsula, the Mackinac Straits are geologically located at the rim of the Michigan basin".

With reference to Fig. 4-6, it is emphasized that the Detroit area too is geologically located at the rim of the Michigan basin. The inset shows the isopachs of the Salina salt south of Windsor, Ontario (PEARSON, 1963, Fig. 15); the A1 and A2 salts are missing east of the Detroit river.

The solution structure of Fig. 4-5 apparently is connected to the salt-free area east of the Detroit river which separates the main Salina

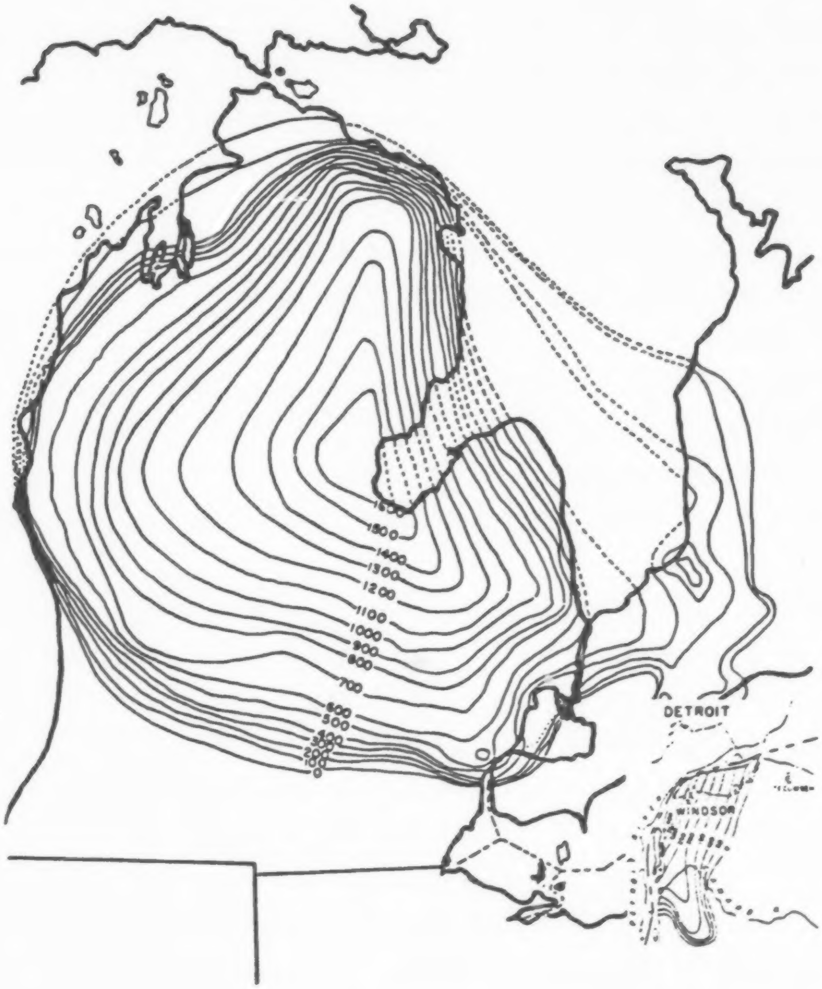


Fig 4-6 Salina isopachs
See text for explanation.

basin from the small sub-basin south of Windsor indicated by the isopachs on the inset, Fig. 4-6. It is re-emphasized that approximately 200 feet (61 m) of B salt were removed from this area by natural solutioning shortly after its deposition, prior to the deposition of following salt sequences.

As stressed by JARON (1970, p. 422, see the quotations at the beginning of this sub-section), the resulting subsidence trough was filled with solutioning residue, and with subsequent sediments. Apparently, the subsidence trough collected sediments as frequently observed on local depressions in areas of relatively fast sedimentation. In other words, peneplanation began immediately.

Any adequate interpretation of the origin of the solution structure of Fig. 4-5 must account for the paleo-geographical situation at the time of deposition of the Salina: the Michigan basin was the terminal basin into which sea water was travelling through forebasins in the Appalachian region; a map showing areas underlain by Salina salt, and areas of apparent non-deposition can be found in PEARSON (1963, Fig. 10). Referring to DELLWIG (1955), the writer (l.c., p. 218) stresses "some differences between salt deposits of the deeper parts of the (Michigan) basin and the marginal deposits such as at Detroit, although both are layered deposits".

"The anhydrite-dolomite laminae are the result of intermittent influx of water or brine into the basin carrying $CaCO_3$ and $CaSO_4$. Thick salt beds represent periods of influx of brine, which was almost depleted in $CaSO_4$ and $CaCO_3$, into a uniformly subsiding basin". These conditions are similar to those governing salt and potash deposition in most major salt basins as outlined in Chapter I/2.

Access to the Michigan basin for sea water influx during the first evaporation cycles was controlled by reefs "which stood up in relief as hills on the sea floor at the time of early Salina deposition" (PEARSON, 1963, p. 218). Details can be found on maps presented in the reference publication; apparently, the main influx into the Michigan basin was controlled by reefs in Southwestern Ontario at some distance from the Detroit/Windsor area (l.c., Fig. 15).

The solution structure shown in Fig. 4-5 may represent a channelway along which fresh water was travelling into the main Michigan basin, dissolving the salt of the B unit, the resulting depression being filled with solution residue and subsequent sediments.

Referring to the structure maps, Figs. 4-4 and 4-5, JARON (1970, p. 425) re-emphasizes the fact that the B salt "thins from about 190 feet to less than 20 feet" (58 to 6.1 m), "and the thickness of the overlying insoluble unit (Unit G plus B rubble) increases from 140 to more than 290 feet" (42.7 to 88.4 m).

Fig. 4-5 "shows the salt to be deeply sculptured by solution thought to have occurred during B and C time. Within the area shown by our data points, we can see one distinct channel; others probably lie outside of the area covered. This channel has its 'head' in the downdip direction, implying, in this area, subterranean updip solution".

This interpretation of the data shown in Figs. 4-4 and 4-5 is untenable for the following reasons:

(1) The solution structure of Fig. 4-5 is branching into two 'heads', one pointing north, the principal 'head' pointing west, both 'heads' pointing towards the main Michigan basin, see Fig. 4-6. Large marginal areas of the main basin apparently were exposed when the brine volume decreased upon concentration and salt precipitation, see I/2.1. In other words: during the deposition of the B salt, subterranean updip solution could not take place as the brine level in the Michigan basin sank deep below sea level; the sea level may have been maintained in forebasins as suggested by the anhydrite-dolomite laminae in the B salt.

(2) Apparently, the solution structure of Fig. 4-5 indicates channels in which fresh sea water was flowing subterraneously towards the main Michigan basin, dissolving salt along its travelway and becoming more or less saturated when entering the basin. The salt content of the flowing solutions increased in the northerly and westerly directions which are apparent on Fig. 4-5. This explains why less salt was dissolved near the 'heads' of the solution structures. However, the subterranean solutioning occurred downdip, the solutions draining into the main Michigan basin.

JARON (1970, p. 425) is placing particular emphasis on a core "taken in the middle of the solution feature (which) shows intense brecciation for a distance of 90 feet (27.4 m) above the salt top" of Unit B. The photograph of two pieces of the core - diameter approximately 3 inches (7.6 cm), lengths 7 and 11 inches (17.8 and 27.9 cm), respectively - "shows an example of the breccia. The groundmass varies, but (on the photographs) it is largely a shale-bearing dolomite with sub-angular to sub-rounded fragments of dolomite and anhydrite... These fragments are probably remnants of insoluble stringers which are common in Unit B. Fifty feet (15.2 m) of this breccia is clearly Unit C, the remainder being jumbled Unit B rubble."

"The fifty feet of Unit C has retained its gamma ray/neutron identity and is readily traced throughout the solution structure, its thickness being constant. Brecciation stops in a ten foot thick breccia bed in Unit C. Above this bed is a thickened Unit C (shaly dolomite with minor anhydrite) section."

"Cross bedding and cut-and-fill structures are found indicating a shallow-water depositional environment. A structure map on top of the uppermost brecciated anhydrite mirrors Fig. 4-5, top of the B salt. This infers that intensive solutioning did not begin until the uppermost breccia anhydrite bed was deposited."

The fact that fifty feet (15.2 m) of Unit C can be traced throughout the structure, its thickness being constant, is the key to the correct interpretation of the subsidence process caused by salt solutioning in Unit B.

At the time when "intensive solutioning" began, the sediments above the salt were not yet consolidated; they were affected by early stages of diagenesis in a shallow-water environment which may have been similar to the sabkha environment dealt with in numerous recent publications, see I/2.2.2.

Intermittent exposure may have resulted in what are called "cut-and-fill structures" in the quoted description. The significance of numerous vertical cracks as reported by DELLWIG (1955) apparently is underestimated in the publication under discussion. As DELLWIG and EVANS (1969, p. 953) put it: "The solution of salt to produce local minor unconformities is to be expected near a basin margin, i.e., at Detroit" (and other localities near the eastern margin of the Michigan basin). Petrographic structures similar to those observed in Salina salt are found in the Prairie Evaporites, see Fig. I/2-12.

The following point is particularly stressed: the top fifty feet

(15.2 m) of the fresh sediments above the solution feature of Fig. 4-5 were still soaked with brine; diagenetic processes of unknown nature were in progress. The water-saturated, unconsolidated sediments did not possess material strengths which could have enabled them to bridge any cavity developing in the underlying B salt - if at all sizeable cavities developed at the top of the salt; DELLWIG's (1955) observations and the observations reported in I/4.2 indicate the opposite: even pre-existing cracks were filled with material such as clay and anhydrite particles from unconsolidated overlying beds.

As a matter of fact, the cores of the "solution collapse breccia" shown on the photograph referred to above indicate comparable processes: the groundmass, after consolidation and lithifaction, apparently consists mainly of clay minerals in which fragments of "insoluble stringers" of dolomite and anhydrite are embedded. The largest fragment detectable on the photographs has a diameter of approximately one centimetre, and this is consistent with the mode of origin outlined above: the stringers disintegrated prior to consolidation and compaction by subsequent sedimentation.

The use of the term "fragments" may be questioned by petrographers in view of the mode of origin; the consolidated solution residue as observed in cores definitely should not be called a breccia as this term refers to the breakage of solidified rock material with considerable material strengths - as observed by LANDES (1963) and called the Mackinac Breccia.

It is emphasized that one of the various types of breccia described by LANDES (1963) resembles the solutioning residue described by JARON (1970). Solutioning similar to that described in the preceding discussion undoubtedly took place at the northern rim of the Michigan basin when the volume of brines decreased due to increased evaporation and salt deposition. Apparently, the Mackinac Straits area has been a groundwater discharge area at least since the Silurian when the Michigan basin was subsiding.

As the Mackinac breccias are referred to in numerous recent publications, a detailed discussion appears indicated.

4.3.2 The Mackinac breccia - some re-interpretations

LANDES (1963) expects salt caves to be formed by leaching of salt deposits near the surface. His descriptions are quoted in the following attempt to clarify these matters.

Under the heading "SALT CAVES", the writer (l.c., p. 68) makes the statement: "Because of the solubility of salt, one would expect caves to be abundant, especially where a salt body lies above the water table and therefore comes into contact with under-saturated migrating waters. However, the same extreme solubility also is responsible for the fact that in most areas the salt has been dissolved to such depths that salt caverns are not visited by man in the same way as are limestone caverns. Numerous drilled wells around the rim of the Salina salt basin in Michigan and Ontario, and in other areas, where the structure brings the rocksalt close to the surface, have penetrated small caves in the salt measures (LANDES, 1945)".

As the reference publication "is no longer in print" (l.c., p. 68), it was not possible to assess the meaning of "small caves in salt measures". In all probability, the caves were encountered in the non-salt members of the respective evaporite sequences.

It is re-emphasized that small cavities frequently are encountered in evaporites other than salt rocks; however, cavities in deeply buried salt are closed by creep if their contents can escape, see I/3.6.2 and 4.2.

On the other hand, it cannot be questioned that large-scale salt solutioning causes overlying formations to subside; large surface depressions may develop. It also cannot be questioned that localized solutioning of salt along pre-existing fractures may result in sudden settlement of blocks of the overburden, provided there are formations present which can bridge large spans across areas of salt solutioning.

In this regard, there is no difference between various processes of removal of overburden support. Most geologists speak of block faulting when dealing with what LANDES (1963, p. 70) calls "megabreccia": "blocks of sedimentary rock with horizontal dimensions ranging from a few feet to hundreds of feet have been dropped and tilted...A fault bounding one such megabreccia block can be seen in a cut" (at an identified location).

The "local and sudden type of collapse, producing the transformational breccia" and "megabreccia" (l.c., p. 72), requires quite extensive caves if attributed to "failure of cavern roofs". Such extensive caves definitely cannot persist in salt deposits under the load of a few hundred metres of overburden - not to mention the fact that most flat-lying salt beds, particularly those of the Salina, are characterized by roof rocks which tend to break up into "sidewalk-size" and smaller slabs, as shown by JARON (1970) and PIPER (1970).

The "distinct possibility of undermining fault blocks" is demonstrated by JACOBY (1970, pp. 466-469, figs. 2-4); the fault block referred to has the diameter of approximately 200 ft (60.1 m), so it is still relatively small in comparison with fault blocks suddenly settled by potash mining, see Chapter 2.

In contrast to such fault blocks, the fragments of the Mackinac breccia "range in size from powder to rock slabs over 20 feet in maximum dimension" (LANDES, 1963, p. 70). "Stratification can be seen in the larger fragments, with dips from horizontal to vertical. There is no relationship between the orientation of adjacent fragments".

Those familiar with roof falls in conventional room-and-pillar potash mines and with intentional roof caving methods applied in potash mines will give a similar description of the "debris" observed underground in dry mining operations after roof failure. The "debris" observed in solution mining operations may fit the quoted description for a limited period of time: such "debris" disintegrates more or less rapidly when its components undergo mineralogical and petrographical changes due to water adsorption. Even moist air is known to cause such disintegration; for details, the interested reader is referred to related publication (e.g., BAAR, 1954c; BRAITSCH, 1962, 1971).

Under the heading "SURFACE COLLAPSE", LANDES (l.c., p. 68) refers to surface depressions which develop in areas of shallow rocksalt when salt is removed by groundwater; with reference to other writers, such depressions are attributed to collapse of overlying strata. Reference is made to "collapse features resulting from the leaching of gypsum and anhydrite in the Permian rocks of the Texas and New Mexico area", and to "collapse features, including surface depressions, in the Gulf

Coast salt dome area".

It must be stressed that the mechanisms of such "collapses" differ considerably. Surface depressions caused by salt dissolution are not necessarily associated with collapses, as examplified in 7.5.2. The uniform settlement of 50 feet of strata above the solution structure at Grosse Ile provides another example as discussed previously.

On the other hand, sub-surface karstification of gypsum, anhydrite, and limestone is well known for causing local collapses of overlying strata.

The caprock of the Gulf Coast salt domes normally is made up of rather fine-grained material; the leached salt contained only limited amounts of anhydrite and dolomite. At many locations, caprock is missing or poorly developed; the domes are indicated by uplift of the surface rather than by depressions, as discussed in 4.1.

The reader is particularly referred to the subsidence characteristics outlined in 7.1.1 and to the measured surface subsidences dealt with in Chapter 7.

LANDES (l.c., pp. 68-73) describes "ANCIENT COLLAPSE BRECCIAS" as follows: "The collapse of the roof overlying salt caverns, with resultant tumbling downward of the overlying rock into a jack straw arrangement of angular blocks with finer material filling the interstices, is by no means confined to the present erosion cycle. In geologic time, at least as far back as the Silurian, similar conditions existed and widespread collapsing occurred. The rock which results from the compaction and cementation of the collapse debris is known as breccia, and it is by these breccia deposits that we are able to recognize geologically ancient collapsing."

"The Mackinac breccia of the Mackinac Straits region in Michigan is probably the most spectacular, and certainly the most accessible, example of large scale collapse into caverns dissolved in salt in North America...Differential erosion of indurated breccia has produced prominent rock spires...However, the volume of indurated breccia is very much less than the volume of unindurated breccia, which underlies many square miles, with depths up to 700 feet" (213 m).

"Limestone and dolomite are the main rock types in the breccia, but chert and shale are also present. The fragments can be correlated by fossils and lithology with the stratigraphic column for this area. Formations represented are...of the upper Silurian, and...of the lower Devonian. The overlying Dundee rocks are not disturbed."

"Obviously these breccia aggregates, consisting as they do of intermixed rocks from a stratigraphic section hundreds of feet in thickness and millions of years apart in age, were formed by extensive collapse."

Referring to the isopach map, Fig. 4-6, the writer (l.c., p. 71) continues: "The north end of the (Salina) salt deposit has an exceptionally blunt edge, thinning from 1200 feet (366 m) to zero in a short distance. This is a leached rather than a natural (depositional) edge. The original salt boundary was an unknown distance north of the present boundary; the Salina rocks have been truncated by erosion."

"The postulated sequence of events in the Mackinac Straits area" is given as follows:

(1) Submergence of the Michigan basin and deposition of the Salina formation, totalling nearly 2000 feet (610 m) in the Mackinac Straits area according to the stratigraphic column referred to.

(2) Subsequent deposition of dolomites, cherts, and limestones with the total thickness of approximately 1700 feet (518 m).

It is emphasized here that the postulated depth of burial of the uppermost Salina salt amounts to 2000 feet (610 m); for the top of the B salt, another 1000 feet (305 m) are to be added, resulting in 3000 feet (915 m) of overburden. The top of the A salt would have been buried under more than 3400 feet (1031 m) of overburden.

Such depths resemble the depths of the potash mines in Saskatchewan, Canada, and in Alsace/France, with overburden consisting of similar sedimentary formations. Such formations react without delay to salt extraction, as shown in Chapter 7; the impermeability of the overburden is not affected by subsidence; collapse of immediate roof strata - if any such collapse occurs - is utilized in mining methods with intentional roof caving, see 8.2.

For the Mackinac Straits region, LANDES (l.c,, p. 71) postulates:

(3) "Emergence and solution by percolating ground waters of great quantities of salt around the rim of the Salina basin (this activity could also have taken place during earlier post-salt

emergences). A vast series of caves and caverns were formed."

This postulate is not supported by evidence other than fragments of overlying formations which "can be correlated by fossils and lithography with the stratigraphic column for the area."

It is strongly re-emphasized that the solution structure at Grosse Ile indicates relative post-salt emergence. With respect to the groundwater regime around the rim of the Salina basin, the lowering of the brine level in the basin is equivalent to true emergences as postulated by LANDES (1963).

Relative emergences due to lowering of the water level in the Salina basin took place during all major phases of salt deposition.

It appears conceivable to attribute much of the Mackinac breccia to such post-salt events prior to consolidation of the overburden when ground water flow through the salt cover was possible. This is evidenced at Grosse Ile where "vast series of caves and caverns" did not form; the overburden of the B salt partly collapsed, but settled without delay when salt was removed.

Analogous events in the Mackinac Straits area during any period of salt deposition would eliminate the difficulty of explaining salt dissolution by groundwater at depths around 3000 feet (915 m).

LANDES (1963, p. 72) continues the description of the sequence of postulated events as follows:

(4) "Collapse, no doubt taking place over a long period of time, of the cavern roofs. One type of collapse was local and sudden, producing the transformational breccia previously described. The other type was on a more regional scale; failure of cavern roofs in this instance let down great blocks of strata, producing megabreccia."

(5) "Cementation by ground waters circulating through the sink holes of some of the collapse debris, producing indurated breccia".

(6) "Peneplanation followed by submergence and the deposition of the Dundee and younger formations which are not affected by salt solutioning".

The postulated sequence indicates the writer's disregard of the lower water levels during salt deposition in the Michigan basin. As shown by the Grosse Ile solution structure, peneplanation took place by submergence of marginal areas during periods of sedimentation of dolomite and anhydrite strata between periods of salt deposition; early diagenetic processes cemented the compacting solutioning residue.

(7) "The eventual arrival of the present cycle of erosion. Differential erosion resulted in isolating the indurated breccia masses by removing much of the surrounding non-indurated breccia. Wave erosion along the shores of the glacial and present Great Lakes carved some of the cemented breccia into stacks".

Similar stacks were carved out of fine-grained sedimentary functions such as sandstones in many areas all over the world.

The point to be stressed is: LANDES (1963) leaves no doubt of how the stacks of Mackinac breccia were formed: they were created by erosion hundreds of millions of years after the Mackinac breccia were created by salt solutioning during the late Silurian and the early Devonian.

The reason why particular emphasis is placed on the erosional nature of the stacks of Mackinac breccia becomes apparent in the discussion of sinkhole formation, see Chapter 6: in recent publications, LANDES's unmistakable statements regarding the erosional origin of the stacks of Mackinac breccia are completely ignored; the stacks are interpreted as fillings of sinkholes which developed out of small cavities in deeply buried salt deposits. Such sinkhole "chimneys" with diameters of only 100 m or so are believed to have worked their way up to the surface through consolidated and unconsolidated sediments up to, and exceeding, 1000 metres in total thickness.

There should be no need for mentioning such geophantastic ideas. However, some writers postulate that such chimneys are forming at the present time, for example in the Prairie Evaporites of Canada, endangering surface structures and posing serious threats to potash mines.

Such chimneys are postulated to work their way up from depths around 1000 m to near-surface strata where unlimited amounts of groundwater are standing by. Numerous such chimneys are believed to exist; some are believed to work actively their way up to the surface, and the final breakthrough could occur at any unpredictable time. When potash mining would run into such a chimney, it would mean flooding of the mine workings.

The world-wide publicity given such postulates requires the following detailed discussion.

4.3.3 Prairie Evaporites, Canada/U.S.A.

4.3.3.1 Brecciation caused by salt solutioning

Effects of local and regional salt solutioning in the geological past have important implications in potash mining, and even more so in the exploration for oil and gas deposits in the Prairie Evaporite basin of Canada and the U.S.A. Hundreds of publications, most of them concerned with the hydrocarbon potential of structures related to salt solutioning, are dealing with this topic.

This text is not designed to discuss the evolution of geological hypotheses dealing with the significance of salt solutioning in creating promising hydrocarbon structures. A few quotations may outline some of the hypotheses which have been applied to solution features.

Apparently, there are tremendous gaps between hypotheses on which professional geologists are basing hydrcarbon exploration, and hypotheses promoted by earth scientists in teaching positions. Professors tend to oversimplify geological conditions, and to overemphasize their own observations and those reported by students. Quite frequently, writers are in no way qualified to deal with matters as complex as the solutioning of salt deposits. These statements also apply to some geologists in governmental departments who publicize questionable ideas.

One professional opinion on "collapse structures related to evaporites of the Prairie Formation" may be quoted as follows (DE MILLE et al., 1964, p. 307): "The salt deposits of the Middle Devonian...overlie thin carbonates containing reefs. These sediments form part of a depositional sequence starting with thin shales and grading upward to carbonates, followed by evaporites climaxing in potash salts and capped with red beds. This sequence is overlain by similar depositional units in which, however, evaporites are less well developed."

"Because of the excellent subsurface control in this vast gently dipping shelf area, it is possible to recognize structural features that might go unnoticed in more complex areas. Structural highs due to salt flowage are unknown. There are, however, many structural lows which are due to removal of salt by subsurface leaching."

The writers present detailed descriptions of two structural lows, including isopach maps of post-evaporite formations; photographs of cores show breccia in the beds overlying the position of the missing salt. The breccia is similar to breccias found in other areas of suspected salt-leaching in Saskatchewan. Notable features of the breccias are:

(1) their well-defined base coinciding with the top of the strata underlying the Prairie Evaporites; and

(2) their upward extension through two or more formations of differing lithology. In view of this, there is little doubt that the breccias resulted from solution and collapse."

One photograph "shows rock typical of the lower parts of these breccias, in which much of the material is of a fine nature. Some of it, both fragments and matrix, is believed to represent insoluble matter within the original salt."

The second photograph "shows higher parts of the breccia. The fragments are much larger, and there is less relative separation. Where core is available, it shows these breccias grading upward a hundred or more feet and eventually merging with fractured but otherwise unbrecciated strata".

Referring to "detailed isopachs of units overlying the Prairie Evaporites", the writers (l.c., p. 314) "suggest that salt removal may have begun as early as Late Devonian time and recurred repeatedly".

"Careful study of the geometry of the rock masses involved in the deformation indicates that in most cases some structural movement must have occurred beyond that compensating for the salt removal. One may speculate whether basement movements fractured the sedimentary section to create permeability and permit the fluid movements necessary for salt leaching".

The writers conclude "that the Prairie Evaporites have been severely affected by underground solution and that leaching took place while the salt body was buried under thousands of feet of sediments...The structural lows contain solution breccias which are confined to the beds younger than the salt. Significantly, these breccias have not been observed where the salt is present. They do, however, have a widespread occurrence in adjacent areas, which indicates that the Prairie salt originally had a much broader distribution".

"Solution occurred at different geologic ages from Late Devonian to the present". "Both porous reefs and bedrock fractures would supply the necessary circulation channels for the water required in this process".

4.3.3.2 Untenable hypotheses on regional solutioning

DE MILLE et al. (1964), as quoted above, assumes more or less vertical circulation paths through which the salt solutioning brines ascend to the level of near-surface groundwater flow systems. The fact that "the evaporites are now buried under a cover of younger rocks 1000 feet thick in Manitoba, about 5000 feet thick at Regina, and more than 8000 feet thick in North Dakota" (l.c., p. 310), makes it extremely difficult to explain the mechanism which could presently lift heavy salt solutions from the given depths to near-surface groundwater flow systems.

Most geologists who are dealing with these postulated processes ignore the necessity of providing a reasonable explanation of the physics involved, i.e., to explain how fresh water can possibly gain access to the deeply buried salt deposits, how heavy salt solutions are lifted to near-surface groundwater, and how such processes could continue over extended geological periods of time while oil and gas remain underground. No evidence of present natural salt solutioning, such as salt water springs or saline groundwater, was detected at or near the locations of postulated salt solutioning in central areas of the Prairie Evaporite basin.

Referring to the observations by DE MILLE et al. (1964), CHRISTIANSEN (1967, p. 765) postulates that "the solution of salt by groundwater is undoubtedly going on at the present time and future collapses can be anticipated" in the Saskatoon area. "Although collapse depressions have not been observed on the present surface", and although saline springs and/or abnormal salt contents of groundwater cannot be shown, the writer postulates "that the collapse mechanism is a continuing process".

The writer (l.c., p. 757) claims that DE MILLE et al. (1964) "did not investigate the effect of the collapse on younger sediments". This statement cannot be reconciled with the quoted report that "cores show these breccias grading upward a hundred or more feet and eventually merging with fractured but otherwise unbrecciated strata".

The latter observation indicates subsidence mechanisms similar to those documented in Chapter 7.

The collapses took place shortly after the deposition of major salt sequences, or on occasion of true or relative emergences which made the buried salt deposits accessible to near-surface groundwater action.

CHRISTIANSEN (personal communication, October 1977) based the quoted conclusions exclusively on near-surface investigations; salt solutioning was pre-assumed in accordance with reference publications. Referring to "subsidence on mining", the writer (1967, p. 764) postulates that "high angle gravity faults, which dip toward the center of collapse at an average angle of 70°, characterize the mechanism of the salt collapse.

The writer shows several cross-sections through the Saskatoon area and comments: "Although only a few faults are shown, the collapse area comprises undoubtedly a large number of individual fault blocks, which are bounded by high-angle step faults".

The quoted statements show that the writer's "structural solution" is merely an assumption; it is not supported by evidence. As a matter of fact, it is contradicted by the subsidence data presented in 7.2 and by similar data obtained above other potash mines in the vicinity of the Saskatoon salt solution area.

The measurement data on surface subsidences after room-and-pillar mining at depths around 3500 feet (1067 m) show no delay in overburden subsidence which takes place without faulting. Needless to say that faulting would have serious implications for the potash mines operating near the Saskatoon salt solution area.

CHRISTIANSEN (1971) postulates faulting due to salt solutioning at great depths also with respect to very localized solutioning which is believed to result in pipe-like sinkholes (chimneys) with diameters of approximately 100 m. Cylinders with such diameters are postulated to have been downfaulted through approximately 1000 m of consolidated and unconsolidated overburden formations.

According to GENDZWILL and HAINAL (1971, p. 1514), such "small collapse structures present peculiar hazards to potash mining because they are very difficult to detect. There is also danger to roads and buildings should subsidence or sudden collapse occur in the future." Such postulated implications require a detailed discussion, see 4.3.3.3.

With reference to PEARSON's (1963) map of saline springs in Western Canada it is re-emphasized that no saline springs are known in the central area of the Prairie Evaporite basin.

It goes without saying that saline springs are abundant near the outcrops of the Prairie Evaporites where salt solutioning is still in progress.

The reader is urged to compare the photograph of a core from "the more fragmented lower part of the brecciated section" (DE MILLE et al., 1964) with the photographs of cores from the solution collapse breccia found in the local Silurian salt solution structure at Grosse Ile (JARON, 1970) dealt with in 4.3.2. There is virtually no difference in the size of the fragments, their shape, their irregular orientation, etc.; as a matter of fact, a counterpart for every fragment on the former photograph can be found on the latter two photographs.

This amazing similarity is considered as strong evidence of very similar conditions, implying that most of the solutioning in the Prairie Evaporite basin took place during or shortly after the deposition of the salt sequences. Direct evidence of contemporaneous Devonian solutioning is presented in Figs. I/2-10, I/2-11, and I/2-12. More details can be found in the reference publications (WARDLAW, 1968; BAAR, 1974a).

The reasons why many geologists fail to arrive at acceptable interpretations of salt solutioning features in the Prairie Evaporite basin are rather simple: it is overlooked that the volume of brines was greatly reduced when concentrations as required for the deposition of potash were reached. This is demonstrated in Figs. I/2-1 and I/2-2; it means relative emergence of large areas of the basin, and potash deposition only in its deepest parts.

Tectonic events are frequently invoked to explain emergences of salt deposits. As DE MILLE et al. (1964, p. 310) put it: "As the basin became filled, the retreating sea left a thin deposit of red silts and shales".

In fact, however, the opposite took place: the sea invaded the "desiccated deep basin" of deposition of the Prairie Evaporites and raised the brine level. The conditions for carbonate and sulphate deposition were restored until subsequent desiccation phases yielded more salt sequences in deeper parts of the basin.

The time periods during which partly desiccated basins are refilled with sea water were also time periods of leaching processes in exposed areas, i.e., in marginal areas and in high areas within the basin underlain by carbonate banks and reefs.

The resulting processes of leaching and redeposition of salt and potash can be understood only if writers "no longer ignore" the basic solution equilibria of various systems of oceanic salts at different temperatures; the reader is referred to the statements quoted at the end of I/2.1.1.

With reference to Figs. I/2-12 and I/2-13, it is re-emphasized that there is ample evidence of downward migration of solutions through the salt deposits of the Prairie Evaporite basin. However, evidence of rising solutions is missing to date.

HOLTER (1969) presents a critical review of the processes of Prairie Evaporite sedimentation and salt solutioning; his appraisal of solution collapse breccias which "formed as a result of collapse of strata into salt caverns" (l.c., p. 49) is largely based on publications by other writers. The observations by DE MILLE et al. (1964) on breccias are confirmed; the writer stresses that "an important aspect of analysis of these solution collapse breccias is to recognize that the vertical extent of brecciation in no way indicates the amount of salt removed".

The "age of solutioning" is assessed according to numerous reference publications "in terms of four major episodes" (l.c., p. 52); "the extent of salt removal during each is shown" on maps as follows:

(1) During the Middle Devonian, i.e., at the time of deposition of the Prairie Evaporites, only minor occurrences of early solutioning are reported. The writer apparently refers to areas of complete removal of salt, ignoring the partial removal and redistribution of potash by contemporaneous solutioning processes.

(2) Late Devonian solutioning is shown restricted to localized channels and lows near the southern edge of the Prairie Evaporites, and to a few isolated areas.

(3) During the Mississippian-Jurassic, most of the salt removal is shown at scattered localities over much of southern Saskatchewan, continuing the Late Devonian pattern; some solutioning near the north-eastern edge of the Prairie Evaporites is also assumed.

(4) During post-Jurassic times, solutioning of the salt beds and collapse of the overlying strata into sinks and channels is shown as

very extensive, particularly in areas of previous solutioning and along the northern edge of the basin. Specific reference is made to the dating of solution collapse structures by CHRISTIANSEN (1967) as "Recent to Late Pleistocene".

The "mechanism of solutioning" reported by HOLTER (1969) with reference to various publications is of particular interest; most writers apparently assume basement movements (faulting) as the mechanism which triggered solutioning processes.

PARKER (1967) is quoted here as follows: initiation of salt solutioning and consequent development of collapse structures requires "first, the presence below the salt beds of an aquifer with sufficient hydrostatic head to dissolve salt and carry it through the sedimentary section to the sea floor", and second, "the existence of tectonic activity to cause fracturing or faulting sufficient to allow entry of water from the aquifer upward to the salt and then upward to the ocean floor" (l.c., p. 54).

"Salt removal from above", preferentially over thick Winnipegosis carbonate reefal structures, is considered as another possibility of salt solutioning (l.c., p. 55).

The reviewed publications are concerned mainly with vertical movements of salt solutions; statements as to the lateral movement of such solutions indicate wide-spread belief in the hypothesis of intrastratal movement of water from large recharge areas in Montana to discharge areas along the Precambrian Canadian Shield.

This hypothesis is particularly questionable as it postulates continuing migration of meteoric waters down to depths around 8000 to 10000 feet (2438 - 3281 m). At these depths, the waters are postulated to develop into salt solutions which ascend to near-surface groundwater flow systems along the Canadian Shield.

It is difficult to visualize how such intrastratal waters/solutions can bypass the wide-spread areas of earlier solutioning and numerous oil and gas fields.

4.3.3.3 Untenable hypotheses on local salt solutioning

HOLTER (1969, p. 55) refers to hypotheses which postulate: "solution channels became blocked by cemented collapse breccia", so the channels "were shifted laterally to form passages parallel to previously existing ones". Such and similar geophantasy bloomed particularly after the Bengough earthquake which shook southern Saskatchewan in 1972. Some writers called for salt solutioning and collapse at the depth of 8000 feet (2438 m).

HORNER et al. (1973) cite immediate speculation attributed to a geology professor: "some believe the process (of salt solutioning by groundwater at the indicated depth, followed by collapse of "salt cavities") is continuing at present (GENDZWILL and HAJNAL, 1971)". The writers are stressing their "considerable disagreement as to the extent that this mechanism can explain structural problems in Southern Saskatchewan".

An attempt by this writer to clarify these matters in view of the alleged implications on potash mining failed; the publication of a discussion paper (35 pp., numerous figures) in the respective periodical was refused.

Another attempt to clarify these alleged implications became necessary when SCOTT (1974, quotations in CALEMBERT, 1975) raised these matters, referring to CHRISTIANSEN (1967, 1971), DE MILLE et al. (1964), and GENDZWILL and HAJNAL (1971); the well-founded criticism (HORNER et al., (1973) was conveniently overlooked.

SCOTT (l.c., p. 101) re-emphasizes "the importance to potash mines in Saskatchewan because of the danger of mining into one of these porous wet zones (small collapse structures due to local salt solutioning) unexpectedly". "Collapse structures have also been identified beneath the city of Saskatoon. Although most of these features appear to have been developed (CHRISTIANSEN, 1967) in late Pleistocene or earlier, dissolution of salt within the Prairie Evaporite formation may well be a continuing process that could have future engineering consequences".

The writer contends that the assumed collapse structures represent "some of the world's most remarkable topographic collapse features which are the result of dissolution of evaporite deposits".

As suggested by HORNER et al. (1973): such speculations by writers who merely seek publicity must not be taken seriously.

Attempts by this writer to have SCOTT's (1974) misleading statements corrected also failed.

In view of the unilateral publicity given untenable hypotheses, the follow-up publication by HORNER and HASEGAWA (1978) is welcomed. The writers deal with possibly hazardous effects of earthquakes allegedly caused by ongoing salt solutioning as postulated by SIMPSON and LENNOX (1974).

The latter writers contend: "Low-magnitude earthquakes such as that at Bengough...described by HORNER et al. (1973), cause only minor structural damage at the surface, but could have more profound subsurface effects, which might be hazardous in close proximity to mining operations, underground gas-storage caverns, and deep-well disposal operations".

Under the heading "mining operations", the writers refer to RANEK (1970), stating that "subsidence due to mining activities is associated principally with removal of coal and salt from sedimentary deposits... There appears to be only one documented case of land subsidence due to mining in Canada. This is the gradual subsidence and eventual sudden surface collapse at Windsor, Ontario, in 1954 due to the extraction of brines from the salt-bearing Salina Formation (TERZAGHI, 1970)".

The writers consider the observations described in the reference publication as "a fascinating record of a dynamic and obviously accelerating process". It is emphasized here that the reference publication and various other publications dealing with the events at Windsor are in need of correction, see 4.7.

SIMPSON and LENNOX (1974) continue comparing "a number of well-documented examples of land subsidence due to mining outside of Canada" with the postulated effects of ongoing salt solutioning in the central Prairie Evaporite basin, citing as "notable among the historical cases those associated with exploitation of the salt deposits in Cheshire, England".

Such examples of near-surface solutioning due to inadequate operational conditions, see 4.4.2, must not be compared with postulated solutioning at depths exceeding 2000 m. However, published surface subsidence records must be taken into consideration. Such records cover time periods of more than half a century, see Chapter 7, and must not be ignored in "decision making in environmental management" (SIMPSON and LENNOX, 1974; SIMPSON and DENNISON, 1975; DENNISON and SIMPSON, 1973).

In fact, surface subsidence measurements above potash mines in Saskatchewan also show the discussed publications erroneous and misleading.

Surface subsidence measurements were initiated when potash mining operations started at Kalium Chemical's solution mine near Regina; subsidences are measured above most conventional potash mines.

Reference to subsidence measured under entirely different geological and operational conditions can only mislead the reader.

PANEK's (1970) statements quoted in 7.1.1 regarding the problems in comparing subsidences at different locations are re-emphasized.

The most serious shortcoming in the criticized publication (SIMPSON and LENNOX, 1974) is characterized by the statement: "In general (LEGGET, 1973), extraction of minerals in the solid state no longer poses a serious subsidence threat". The writers ignore the inevitable creep into excavations in salt deposits at great depths.

The conventional potash mines in Saskatchewan are operating at depths around 1000 m; the solution mine is extracting salt and potash from approximately twice that depth. Creep into conventional mine openings are known to result in complete closure of mined-out areas within relatively short periods of time, see I/5.2.

Ignoring the proven fact of continuing mine opening closure at relatively high rates. DENNISON and SIMPSON (1973, p. 886), believe "that the potash shaft mines themselves represent about 2 billion cu ft of potential subsurface storage space". SIMPSON and DENNISON (1975) make a similar statement.

In fact, however, the storage space is nil, unless space which is temporarily available in mined-out areas is utilized immediately.

Solid waste disposed in a mined-out panel will be isolated by creep within a few decades. It can be isolated immediately by closing the access entries.

Mined-out areas filled with fluid waste would have to be sealed so that the fluids cannot escape. Such sealing does not involve any unusual technical problems; as a matter of fact, flooded mine workings in salt have been sealed and isolated many times.

However, due to continuing creep closure of the cavities, the fluid pressure in sealed cavities increases until equilibrium with the lithostatic stress field is reached, see Fig. I/3-7. Needless to say that discharge from such isolated disposal areas due to the reasons dealt with in I/4.6 must be prevented.

SIMPSON and LENNOX (1974) ignore these relationships, although comprehensive data obtained in potash mines in the Prairie Evaporites were published in 1971 and discussed publicly on various occasions (BAAR, 1971a, 1972a, other publications). If writers choose to ignore published data, it cannot be helped. However, the resulting ignorance should not be demonstrated again and again in publications.

The criticized writers also ignore published analyses of brines encountered in potash mines in Saskatchewan (BAAR et al., 1971; BAAR, 1972c). A shortened version of the latter report (BAAR, 1974a) triggered the controversies regarding potential danger in potash mines in Saskatchewan which arose at the Fourth Symposium on Salt (PIPER, 1974).

The brine analyses referred to show conclusively that Devonian brines are still present in and near the potash beds mined in Saskatchewan. Fig. I/2-15 represents one example out of dozens of similar local brine seepages into potash mines. These facts demonstrate the scientific credibility of statements such as "the central Montana uplift is the recharge area for meteoric waters flushing the Paleozoic strata of southern Saskatchewan" (DENNISON and SIMPSON, 1973, p. 894).

4.4 NATURAL SALT SOLUTIONING AFFECTED BY BRINE PUMPING

4.4.1 Brining in tabular salt deposits

Man's activities to provide salt for nutrition concentrated for millenniums on natural salt springs. It is not intended to present here an historical record of efforts to increase the productivity of natural salt springs, and to obtain additional brine supplies in areas of natural salt solutioning. Needless to say that the techniques employed in such brine gathering activities improved with the advance of technology, particularly over the past century.

In this text, uncontrolled brine pumping is referred to as wild brining; stepping up such wild brining by adding water to further improve the brine production is termed uncontrolled solution mining, see 4.6.

However, it is not intended to define a systematic difference between wild brining and uncontrolled solution mining; the differentiation is made mainly because of the increasing application of solution mining techniques in areas where natural salt solutioning does not take place at the present time.

There is another reason for presenting published data on uncontrolled solution mining in a separate section: recent experience in what had been considered as controlled solution mining demonstrates uncontrolled effects of salt extraction on overburden formations and, in some cases, on surface structures.

4.4.2 Cheshire basin, England

Many writers consider subsidences and damages to surface structures in the Cheshire area of Northern England as the classical case of uncontrolled salt extraction by pumping natural brines.

Collapse of conventional salt mines contributed to spectacular damage shown by LEWIS (1970); two photographs "show the effects of sudden, catastrophic collapse of the roof of a salt mine in Northwich, Cheshire, following the dissolution of supporting pillars by water which entered abandoned mine workings".

For the sake of clarity, it may be stated that one filling of abandoned workings of a salt mine with fresh water cannot dissolve sufficient amounts of salt to cause collapse. However, if brine is continuously removed, either by pumping or by groundwater flow through the mine workings, support pillars indeed are dissolved. Apparently, the pumping of concentrated brines out of abandoned salt mines contributed significantly to surface damages in the Cheshire salt fields, see Fig. 4-7.

WALLWORK (1974, p. 436) confirms this in his following description of subsidence caused by rocksalt mining: "Limited in occurrence to the area around Northwich, the collapse of the rocksalt mines was almost always caused by solution of the pillars which were left to support the roof of the mine cavities. The mines worked two beds of salt about 30 m thick, taking out about 10 - 12 m of rocksalt from each horizon. The supporting pillars were between 4 - 7 m square, and under normal conditions of working quite adequate."

"However, water was allowed to enter the mines due to bad management, and most were destroyed before 1880. The handful of surviving mines collapsed between 1880-1928, largely due to the fact that many of

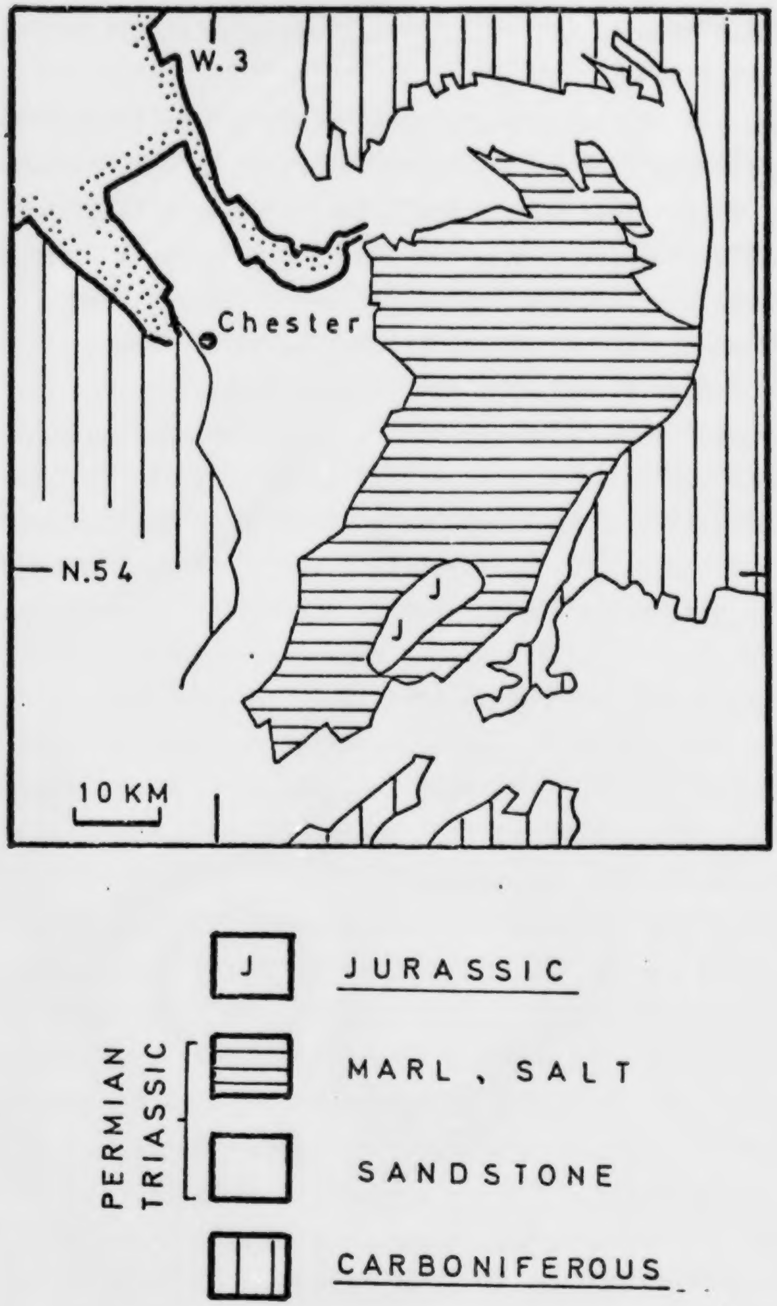


Fig 1-7. Cheshire Salt Basin U.K.

the workings were interconnected and it proved impossible to maintain barriers between them in a locality which was also an area of massive abstraction of brine".

"The collapse of the rocksalt mines would not in itself have presented problems of a general environmental kind; it was the subsequent exploitation of the flood-waters which led to major disruption".

"The most impressive damage was confined to an area of about 200 hectares immediately to the north of Northwich. Here, from about 1873-1907 substantial damage was caused by pumping brine from flooded rocksalt mines, ultimately replacing the natural topography and the various buildings located in the district with a series of man-made lakes".

In view of the world-wide publicity given to postulated natural solutioning processes which allegedly endanger mining and storage operations, see 4.3.3.3, it appears indicated to present the following details of the history of subsidences in the Cheshire basin (WALLWORK, 1974, pp. 435/436): "It is true that subsidence caused by the collapse of rocksalt mines was recorded as early as 1750, and that subsidence due to the abstraction of natural brine first occurred 40 years later, but it was not until the 1870's that substantial problems began to emerge. Between about 1873 and 1923 damage caused by salt working was at its most extensive and impressive".

"During the past 50 years the more spectacular forms of subsidence have given way to subtler forms which, by virtue of their extent and general unpredictability have become important factors conditioning environmental planning decisions. Thus although the damage now caused by salt working does not excite the kind of attention directed towards its nineteenth-century counterparts, it is none-the-less a significant feature of the saltfield's current pattern of development".

Referring to published papers and governmental inquiries, the writer states that "knowledge as to why the various nineteenth-century subsidences took place was greatly limited by ignorance about the geology of the saltfield. The deposits were much more extensive than the worked areas, because the latter were tied to lines of communication, particularly the waterways which linked the saltfield with the port of Liverpool and the south Lancashire industrial region."

"For as long as subsidence stemmed from rocksalt mining, the answers to (geological) questions were academic. But once the major source of damage was attributed to brine pumping, it became important to know to what extent the abstraction of brine at a given point would cause subsidence within the vicinity."

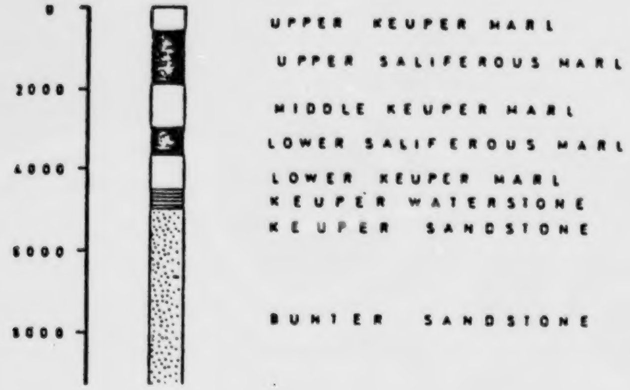
Even so it never has been possible to attribute a particular subsidence to a particular point of abstraction with the degree of certainty that would, for example, stand up to legal scrutiny in a compensation case. For this reason the Cheshire Brine Compensation Board was set up in 1891 (after much strenuous opposition from the salt proprietors) in order to exact a levy from brine pumpers which would form the revenue for claims relating to compensatory damages in the saltfield".

"Subsidence caused by brine pumping was, and indeed remains, the most contentious problem. Whereas it is a simple matter to relate underground mining to surface damage it is much more difficult to do so when subsurface brine runs of indeterminate origin are involved. This is now clear to us, but during the nineteenth century lack of scientific knowledge about the relationship between subsurface geology and the pattern of brine abstraction enabled the salt industry to avoid its responsibilities to the community at large (although in this respect it was probably no worse than most other mineral industries)".

"Over the greater part of the saltfield the brine pumpers secured supplies by tapping natural brine from the wet rock head at depths of between 65 and 130 m";Fig. 4-8 explains the terms used. "The brine runs thereby created did not follow predictable courses, and their effect in terms of surface subsidence was controlled by a number of variables: depth of run, strength or weakness of overlying strata, distance from the surface, and relationship to the surface topography were the most important factors".

"If the subsidence occurred along the line of a water course, permanent lakes were formed (termed 'flashes' in Cheshire), and some particularly impressive ones developed in the Weaver valley south of Winsford during the closing years of the nineteenth century (see Fig.4-9). During the period since 1930, similar lakes have also formed in the Sandbach area" (see LEWIS, 1970, for location map).

"Elsewhere, subsidence of this type might result in nothing worse than the deterioration of meadowland as troughs and small sinkholes



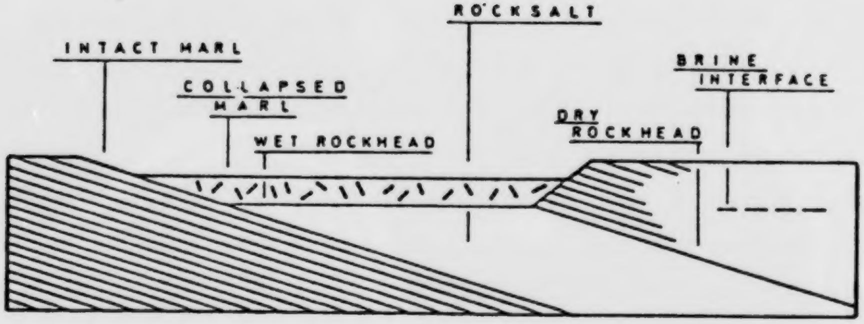


Fig 4-8 Cheshire salt area, England.
geological sequence and
section.
See salt [illegible]

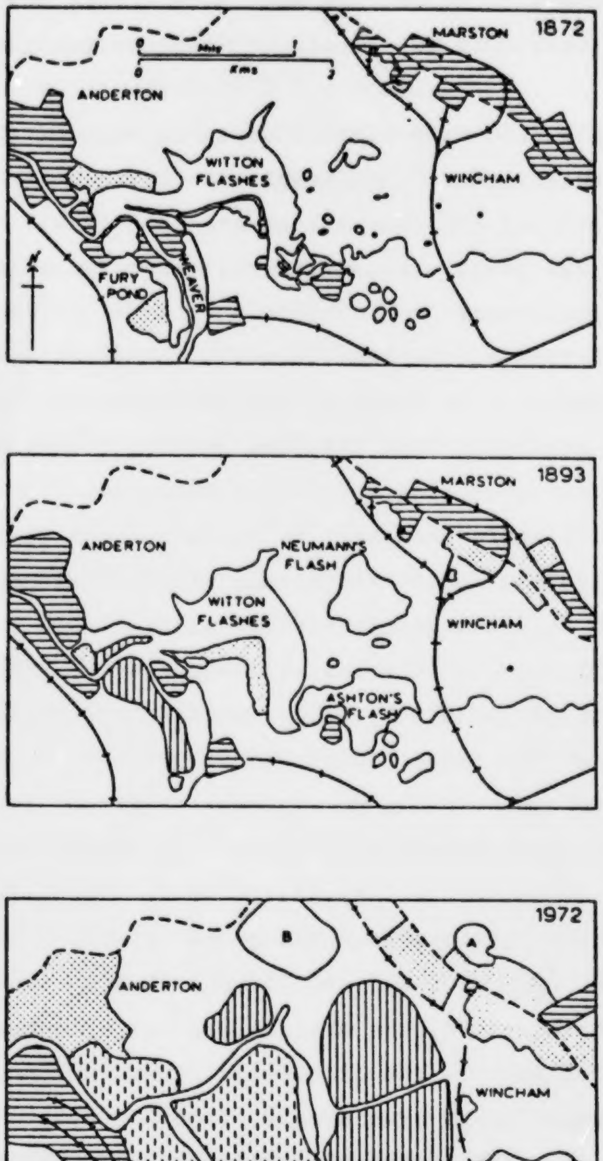


Fig. 4-9. Development of surface disturbances Cheshire salt basin (WALLWORK 1974)

formed, but in urbanized areas very serious damage could, and did result from brine pumping subsidence. In Northwich hardly any of the buildings erected before the end of the nineteenth century survived damage from subsidence".

WALLWORK (l.c., pp. 438-440) provides details of the environmental planning, emphasizing that "the Cheshire salt field is not located in a barren desert, and all the indications are that it will continue to expand as part of the great urban-industrial complex centered on the Liverpool-Manchester axis".

"During the 1970's, the salt industry in Cheshire will be obliged to phase out natural brine pumping, and to substitute some form of cavity solution mining". "The planning authority would prefer to see the ICI method (of controlled solution mining, see 7.5.3.) adopted, which on the basis of 45 years empirical evidence is best suited to the region".

The writer refers to investigations of the Geological Survey in the 1960's which "have revealed that the saltfield is both more extensive and workable to greater depths than was supposed...Much of the newly discovered salt is particularly well suited to controlled extraction by one or other of the solution mining techniques".

Readers interested in the geological structure of the Cheshire basin and related groundwater flow patterns are referred to HOWELL and JENKINS (1977). These writers emphasize that, "at their maximum development, the rocksalts are represented by an upper and a lower sequence, respectively 1300 feet (400 m) and 625 feet (190 m) in thickness".

Referring to Fig. 4-8, the writers report: "In general, at depths down to 600 feet (180 m)", the glacial drift, which "can exceed 330 feet (100 m) in thickness where it conceals 'fossil' valleys", contains cavities filled with brines under artesian heads. "At greater depths the rocksalts are usually intact, the 'dry rockhead' condition".

HOWELL and JENKINS (1977) "propose an initial classification of landforms which are associated with rocksalt subsidence in Cheshire, based on their morphology. It recognizes these landforms as stages in a geological cycle which is heavily dependent upon hydrogeological controls. We consider that each landform in the cycle has a general suite of properties in terms of dimensions, shape, and rate of change".

The writers report "linear hollows up to 780 feet (240 m) in width and 5 miles (8 km) in length". "These generally have a central trough-like section some 190 feet (60 m) wide bounded by convex slopes. Such hollows are related to the strike or dip of the salt beds, or point radially towards a major centre of brine pumping".

Regarding the mechanism of subsidence due to salt dissolution by groundwater, the writers make some important statements which are quoted as follows:

"Fully saturated brine has a relative density of 1.2 and freshwater floats on such brines with a well-defined interface, which in the field is often less than 33 feet (10 m) thick. Therefore, solution of rocksalt depends not only upon the presence of freshwater or under-saturated brine, but also on the continual removal of any developing protective envelope of saturated brine".

"If these conditions do not occur then the solution process is effectively terminated, for the high density brines are not displaced. Diffusion processes across the interface are minimal".

HOWELL and JENKINS (1977) provide evidence of well-defined interfaces brine/freshwater, confirming similar observations made elsewhere; the protection against further solutioning provided by relatively thin layers of saturated brine results in termination of natural solutioning processes at relatively shallow depths below which groundwater flow is insufficient. Their observations are particularly emphasized in view of rather utopic hypotheses criticized in 4.3.3.

The conclusions drawn by HOWELL and JENKINS (1977) are quoted as follows:

"Pleistocene injections of freshwater are considered to have initiated" the described landforms "which have been re-activated and supplemented by man-made perturbations in the groundwater regimes and are likely to continue well into the future".

"Although predictions of the locations, timing and magnitude of these subsidences cannot be made with any of the precision already possible in coal mining districts, we do not accept that rocksalt subsidence is totally capricious. Indeed, we consider that the recognition of mechanisms and some measure of order in the subsidence features forms a rational basis for future studies, which must be directed towards prediction and control".

4.4.3 Wild brining at the top of salt domes, Germany

4.4.3.1 Geological situation

It is impossible to present here a review of the several hundred publications which are dealing with the geology of salt domes in NW-Germany. Fig. I/2-31 shows the distribution of the salt domes, Fig. I/2-34 demonstrates typical internal structures as encountered in numerous potash mines.

The effects of natural salt solutioning at the top of salt domes are described by HERRMANN and HOFRICHTER (1973) as follows (translated and shortened, references not included).

The writers emphasize the extra-ordinary thicknesses of the salt sequences of the Zechstein (over 1000 m); in some areas an underlying sequence of salt with high contents of insolubles has also thicknesses over 1000 m. Difficulties in storage caverns in the latter salt formation are dealt with in I/4.2.4.4.

These "plastic" masses of salt were mobilized in the geological past, see I/2.5.4. The writers note that some salt domes ceased to rise and are now buried under thick overburden formations which were subsequently deposited. Many other salt domes continue to rise, and the top of the domes is affected by near-surface groundwater. This process is termed "subrosion" which "ends at the salt table; shallow, broad depressions can form at the Earth's surface as a result of the removal of the salt in solution".

The writers grossly oversimplify in their statement that the caprock which resulted from solutioning processes at the top of salt domes consists of "residual gypsum" which is "frequently karstified". The caprock also contains the insoluble material originally present in the rising salt masses. Gypsum is present where the amount of water was insufficient to dissolve all of the $CaSO_4$, while the salt was dissolved and removed.

As shown in numerous publications, the original anhydrite beds of the Zechstein sequence are only partially dissolved even at locations where they were in contact with groundwater for geological time periods. The gypsum residue exhibits typical karst features.

A glance at Fig. I/2-34 reveals that thick "residual gypsum" will only be found at locations where the rising salt masses brought the so-called Main Anhydrite into the reach of groundwater. Such isolated location are haphazardly distributed in the caprock of German salt domes.

This is an essential difference in the composition of the caprock of German salt domes compared to the caprock of salt domes in other areas, e.g., in the U.S. Gulf Coast region. This difference must be borne in mind when comparing actual and postulated karst features in caprock of salt domes.

HERRMANN and HOFRICHTER (1973) report on man-made "subrosion" above some salt domes in NW-Germany: Over extended periods of time, brines were pumped from the top of salt domes; in this way, salt dissolution and resulting differential surface subsidence were considerably accelerated.

In a fortunate coincidence the writers refer specifically to the Benthe salt dome near Hannover. The Ronnenberg potash mine, recently lost by disastrous flooding as mentioned in I/5.5.1, had been operated for many decades in the southern part of the Benthe dome.

Most of the surface damage during and after the flooding was not caused by subsidence due to salt extraction by either conventional dry mining or brine pumping. Damaging surface subsidence was caused by the rather sudden withdrawal of groundwater from karstified caprock; some experts accelerated the flooding by drilling boreholes from the surface into the mine workings. Needless to say that details are not published by the notorious multi-writers involved in the mistake.

4.4.3.2 Benthe salt dome near Hannover

The Benthe salt dome is approximately 8 km long and 2 - 3 km wide. Three potash beds were extracted in the Ronnenberg mine, see Fig. I/2-34, and in the adjacent Hansa mine. Both mines ceased potash extraction some years ago. The open space left behind in the dome when potash mining ceased may well exceed 10 million m^3; for the Ronnenberg mine, the figure of 6.5 million m^3 was mentioned in the news media on occasion of the flooding in 1975.

According to HERRMANN and HOFRICHTER (1973), the highest openings of the two potash mines are located at the depth of approximately 400 m; the top of the salt was encountered at depths exceeding 100 m, see

Fig. 4-10. The writers emphasize that the surface above the salt dome represents a plain dotted with numerous subsidence troughs without a water outlet at the surface; some of the troughs are considered as the result of salt solutioning during the more recent geological past, some are considered older, having been filled up with younger sediments.

The writers refer to numerous boreholes drilled at the beginning of this century and discussed in publications. The top of the salt was encountered at depths of 120 to 170 m below the surface; the writers contradict themselves when calling the top of the salt a subrosion plain at 60 - 65 m above MSL.

The gypsum caprock is overlain by unconsolidated Tertiary and Quaternary sediments with variable thicknesses, see Fig. 4-10.

Salt springs are known since 840; approximately 1000 years later, in 1832, commercial salt production began. The writers consider the salt springs as an indication of natural salt solutioning which results in approximately 1 mm/year of general subsidence above the salt dome.

Localized subsidences far in excess of the assumed general subsidence are attributed to brine pumping. Referring to Fig. 4-10, the writers emphasize that saturated salt brines were encountered only immediately above the top of the salt. For example, the borehole E III yielded brine with only 10% NaCl at the depth of 125.44 m; at the depth of 126.99, just at the top of the salt, the NaCl-content reached 26%.

The writers emphasize the varying thicknesses of the gypsum caprock; the minimum is given as 5 m, the maximum as 150 m. The top of the caprock is encountered at depths of 15 - 160 m below the surface. Apparently, the caprock is severely karstified; the cavities are filled with unconsolidated sediments. Small surface craters, rarely exceeding 5 m in diameter, formed occasionally. One such crater had the diameter of 20 m.

An attempt was made to locate a possibly related cavity by sonar-logging of the old drillhole G II of Fig. 4-10. A cavity with the maximum dimension of 20 m was indicated between the depths of 110 and 145 m. The writers assume a continuation of this cavity towards the surface.

An apparent error in drafting at the location of borehole G II should have been corrected: the hole left the gypsum caprock at the

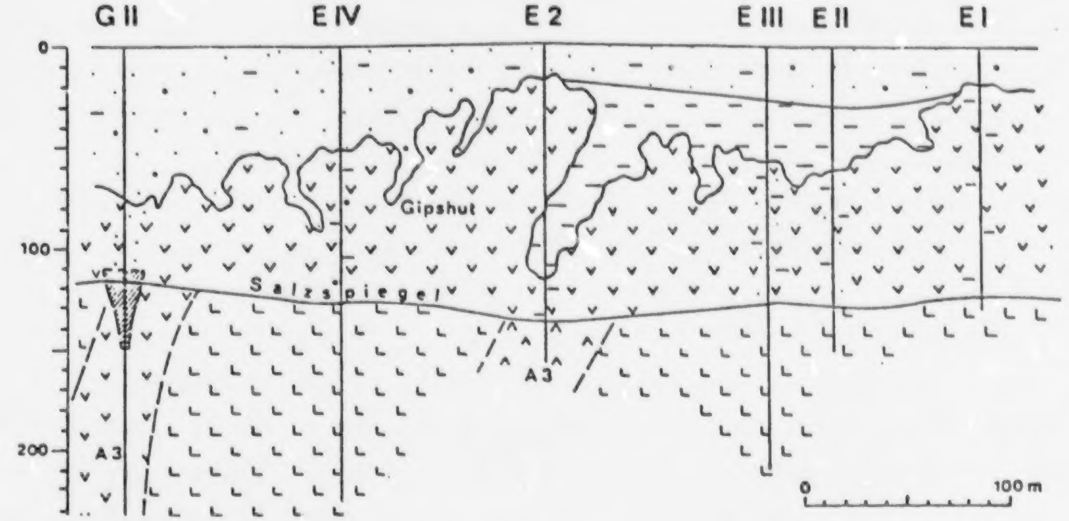


Fig. 4-16 Caprock on the Benthe salt dome [illegible]
[illegible] 1973

depth of approximately 120 m and continued in the A 3 anhydrite (Main Anhydrite), as did the borehole E 2; therefore, the symbols for A 3 should be the same at both locations.

Discussing the possible causes of measured surface subsidences, HERRMANN and HOFRICHTER (1973) report that two million m^3 of solid salt were removed from the top of the salt dome by wild brining since 1832. Ignoring the fact that more than 10 million m^3 of openings were created within the salt dome by the two potash mines, the writers attribute differential subsidences of up to 14.5 cm over 16 years to the brine pumping activities.

The maximum subsidences did not occur at the location where brine was pumped, but at the distance of 800 m. The writers cite "inhomogeneities" of the caprock as the possible cause, probably referring to linear karst features as different solubilities are also mentioned.

The writers fail to explain why the groundwater drawn to the location of the pumps dissolved salt preferentially at the distance of 800 m. On the other hand, the writers also postulate cavities of unknown size in the immediate vicinity of the pumpholes.

Stressing that the measured high subsidence rates decreased when the brine pumping was discontinued, the writers consider the possibility of future surface cratering because of the intensive karstification of the caprock. Additional danger to surface structures is attributed to the possibility that the postulated cavities in the salt near the pumps might collapse successively and eventually break through to the surface.

According to news reports on occasion of the flooding of the Ronnenberg mine in 1975, surface cratering started near the mine shaft, i.e., at considerable distances from the area previously affected by wild brining. The boreholes drilled from the surface into the mine workings were supposed to withdraw the groundwater from distant areas in order to ease the effects on buildings near the mine shaft.

In this respect, the drilling which accelerated the flooding considerably appears to have been successful. However, cratering at distant locations occurred unexpectedly, although foreseeably according to the observations by HERRMANN and HOFRICHTER (1973).

It remains to be seen if a comprehensive account of the events will be published to clarify the questionable assumptions made in the reference publication, and in other publications.

4.4.3.3 Lüneburg salt dome near Hamburg

The surface of the Lüneburg salt dome is a nearly circular area of approximately 1 km^2 underneath the city of Lüneburg. Geological details can be found in publications (SCHMIDEK, 1955; DRESCHER et al. 1973).

The former writer considers the so-called Kalkberg, see Figs. 4-11 to 4-13, as the geological centre of the top of the salt dome; it consists of gypsum. The gypsum masses represent an isolated hill which was partially removed by extensive quarrying. Apparently, the original Main Anhydrite is present at unknown greater depths.

In contrast to the surrounding area where salt dissolution takes place, the Kalkberg shows no subsidence (SCHMIDEK, l.c., p. 842). DRESCHER et al. (l.c., p. 3) report uplift by 1 - 2 mm/year, attributing it to continuing rise of the salt dome, and to progressive gypsification of the original anhydrite.

East of the Kalkberg, the top of the salt is encountered at depths of 40 - 45 m below the surface, i.e., at approximately 23 m below MSL.

West of the Kalkberg, the depths to the salt are up to 58 m, 37 m below MSL. DRESCHER et al. (l.c., p. 2) report depths to 70 m of the top of the salt.

The latter writers (l.c., pp. 2/3) present the following data on natural salt solutioning at the top of the Lüneburg salt dome: for more than 1000 years, natural salt springs were utilized for salt production; the locations of numerous springs, most of them at the eastern periphery of the salt dome, are shown on a map. Due to natural salt solutioning, an area south of the Kalkberg sank below the groundwater level. During the 14th century this area within the city limits was filled up and subsequently utilized for the construction of buildings.

The writers fail to present data on the brine pumping operations which apparently contributed considerably to the reported surface damages. Since 1949, a total of 169 buildings had to be condemned; some new buildings already show damages attributable to differential subsidence.

Controlled solution mining from depths of 500 m was introduced in 1961. No details are reported.

The following maps of measured surface subsidences show the typical

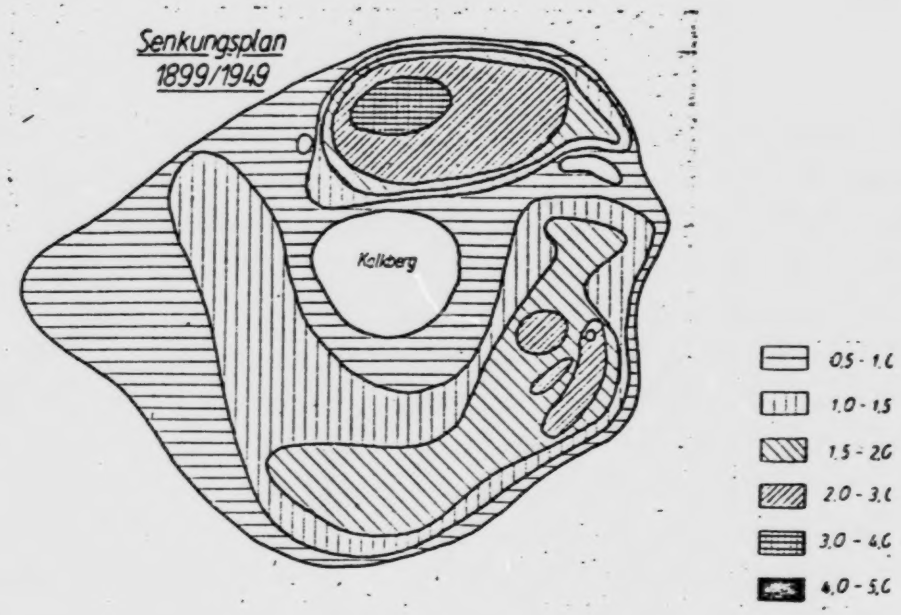


Fig. 4-11: Lüneburg salt dome, vertical movement
1899 - 1949 (SCHMIEDER, 1955)

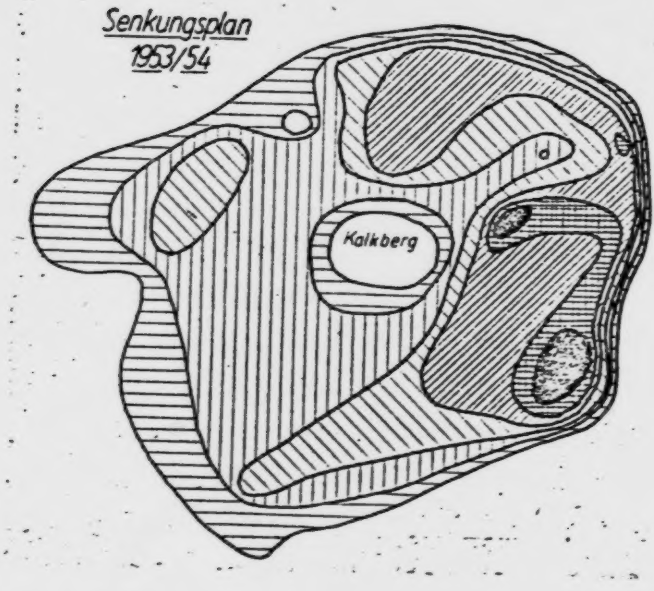


Fig. 4-12: Lüneburg salt dome, vertical movement
1953-1955 (SCHMIEDER, 1955)

subsidence characteristics of Fig. 7-1. DRESCHER et al. (l.c., pp. 3/4) report positive and negative horizontal displacements as observed above coal mines.

SCHMIDEK (1955, pp. 842) states that horizontal displacements were measured for the first time in 1949. The writer reports observations of considerable horizontal displacements; at one location, horizontal compression by 0.78 cm/year was observed over 23 years. A church suffered heavy damage from subsidence; horizontal displacements totalling 48 cm occurred from 1886 to 1951.

For the latter case the writer emphasizes displacement towards the centre of a separate trough with high subsidence rates.

The contour lines of Fig. 4-11 indicate average vertical subsidences measured over 50 years prior to 1949. In 1899, 16 benchmarks were available; at the time of writing, approximately 300 benchmarks were surveyed every year to pinpoint areas of differential subsidence.

The writer stresses the non-uniform solutioning at the top of the salt dome, referring specifically to the elongate subsidence trough north of the Kalkberg which is clearly separated from the rest of the subsiding area. The maximum subsidence rate in the centre of this separated trough is given as 7.79 cm/yr (l.c., p. 839), i.e., the absolute subsidence amounted to 3.9 m over 50 years.

Subsidence rates of such magnitude, and even greater average subsidence rates in other isolated areas shown on Fig. 4-12 cannot be attributed to natural salt solutioning which would have drowned the city of Lüneburg a long time ago. These separated troughs with high subsidence rates are clearly related to brine pumping; the contours reflect the directions of flow of groundwater which dissolved salt to become saturated brine when approaching the pump wells.

There is an apparent analogy to the early development of the subsidences in the Cheshire salt fields, see 4.4.3.2. However, it makes quite a difference to drown parts of agricultural areas or to drown parts of an old city.

SCHMIDEK (l.c., p. 842) stresses the fact that, in some areas of the city of Lüneburg, the groundwater level is encountered only 2 m below the surface; "if the subsidences continue, the whole area will be covered by a lake".

The introduction of cavity solutioning at the depth of 500 m in 1961 according to DRESCHER et al. (1973) had little influence on the subsidence pattern that developed due to the preceding pumping practices. This is apparent from Fig. 4-13 which shows the subsidence contours 1961 - 1971. It should be noticed that Fig. 4-13 indicates absolute subsidences instead of subsidence rates as shown on the two preceding figures.

Apparently, localized troughs of maximum subsidence developed along the eastern edge of the salt dome. These localized troughs do not show on the two preceding figures because of the limited number of benchmarks mentioned above. In other words: Fig. 4-13 indicates more precisely the development of localized areas of subsidence due to localized removal of salt; apparently, the groundwater flow patterns in the vicinity of the local troughs of maximum subsidence are significant.

An apparent error in the legend of Fig. 4-13 is to be corrected: according to the legend, more than 300 cm of subsidence occurred in the centres of the two isolated subsidence troughs near the north-eastern edge of the salt dome over the preceding 10-year period; the average yearly subsidence would amount to 30 cm/yr.

The legend must read "over 30 cm", "20-30 cm", and "16-20 cm". The rest of the legend is correct, beginning with 1 - 2.5 cm subsidence shown at the peripheries of the salt dome and of the Kalkberg, respectively.

DRESCHER et al. (l.c., p. 3) emphasize the apparent difference in the distances of the contour lines at the western edge of the salt dome and at the eastern edge, respectively. There is no sharp morphological boundary detectable at the western edge, while the eastern edge is characterized by so-called fracture lines. The writers elaborate further on such fracture lines with reference to seismic investigations, delineating zones of tension and compression which generally run parallel to the eastern edge of the salt dome. For details, the reader is referred to the reference publication.

The writers (l.c., p. 3) suggest that the higher elevation of the top of the salt dome at its eastern edge might be the reason why preferential solutioning took place at the eastern edge.

DRESCHER et al. (l.c., p. 3) provide exact data on the development

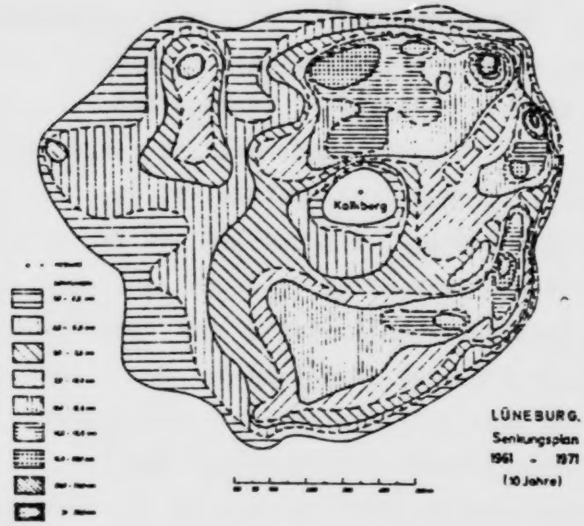


Fig 4-13. Lüneburg [illegible] [illegible] subsidence [illegible] 1961-1971 (DRESCHER et al. 1973) see text for corrections

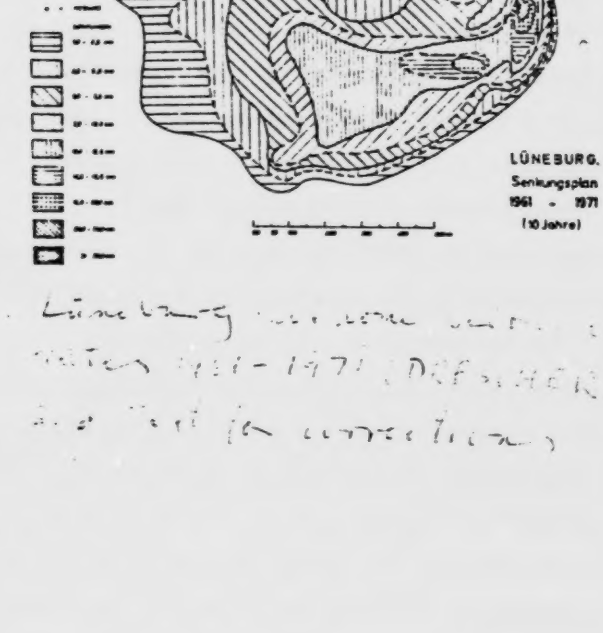


Fig [illegible] Lüneburg [illegible] [illegible], [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] see text for corrections.

of the horizontal compression rates at the location mentioned previously after SCHMIDEK (1955). Fig. 4-14 shows these horizontal displacement rates for the observation period 1899 - 1971. The total displacement over seven decades indeed amounts to an average compression of 1 cm/yr. However, the curve shows only approximately 10 cm of compression for the first three decades; close to 40 cm occurred over the following two decades.

In other words, the compression rate increased considerably and reached an average of 2 cm/yr; it levelled off to much smaller values for the last decade prior to 1971.

The writers fail to give the exact location of the observation point. According to DRESCHER et al. (l.c., p. 3) the observation point is located near the centre of the deepest separate subsidence trough shown at the northeast corner of the salt dome, see Fig. 4-13.

The decrease in horizontal displacement rates over the last decade of Fig. 4-14 co-incides with the introduction of controlled solution mining in 1961. This co-incidence leaves no doubt of the cause of the development of elongated troughs with high subsidence rates: as outlined above, local groundwater flow patterns, depending heavily on karst features, resulted in preferential leaching of salt along pathways towards brine pumping wells.

DRESCHER et al. (l.c., p. 3) present Fig. 4-15 to show the vertical displacement near the observation point for Fig. 4-14, reporting 1.95 m of total subsidence from 1899 to 1971. According to Fig. 4-13 (corrected values), approximately 30 cm of vertical subsidence should have occurred during the last decade prior to 1971.

However Fig. 4-15 shows 30 cm of vertical displacement over at least two decades prior to 1971. The decrease in the vertical displacement rate near the end of the observation time matches the decrease in the horizontal displacement rate.

In contrast to Fig. 4-14, the writers show the vertical displacement rate constant for the first three decades. The absolute vertical displacement reached 120 cm in 1929, so the vertical subsidence rate calculates as 4 cm/yr. This rate cannot be reconciled with Fig. 4-11 on which maximum subsidence rates of 3 - 4 cm/yr are shown right north of the Kalkberg. The rate shown for the location of the observation point of Fig. 4-15 given as 1 - 2 cm/yr, depending on the exact location.

These inconsistencies indicate a high degree of over-simplification, and perhaps too much phantasy in constructing the Figs. 4-11 through 4-15. However, at least DRESCHER et al. (1973) recognize the significance of the subsidence characteristics shown in Fig. 7-1. The writers emphasize the relationship between the tension zones of subsidence troughs and sinkholes. On one of their figures (l.c., fig. 7) they show about a dozen of the sinkholes which formed over the past century lined up along the eastern boundary of the salt dome, i.e., in the tension zone of the general subsidence trough shown above the salt dome.

For unexplained reasons, the writers show a narrow compression zone less than 100 m wide running generally in the N-S direction some 100 m east of the Kalkberg. The northern end of this compression zone is shown pointing towards the location of the maximum subsidence near the north-east corner of the salt dome. Fig. 4-14 demonstrates considerable horizontal compression in the centre of the local subsidence maximum near the north-east corner of the salt dome.

However, the existence of a narrow compression zone crossing most of the subsidence contour lines of Fig. 4-13 appears rather questionable in view of the following details given on the local conditions around the observation point of Figs. 4-14 and 4-15.

DRESCHER et al. (l.c., p. 3) emphasize that 11 cm of horizontal tensional displacement were measured from 1958 to 1970 at the distance of only 40 m from the observation point of considerable compression, Fig. 4-14. Referring to the picture of a building, the writers report that a sinkhole formed on May 1, 1931, under the building which suffered extensive damage.

Another sinkhole formed in 1914 at the same location. A drillhole detected cavities at depths of 35 - 40 m. The writers attribute such cavities to the intensive karstification of gypsum above the top of the salt dome.

Referring to another sinkhole with the volume of 120 m^3 which formed in 1970 at the eastern edge of the salt dome, the writers emphasize an increase in vertical subsidence rates of nearby benchmarks over the preceding years. At one benchmark, the vertical subsidence rate increased from 3 cm/yr in 1957 - 1968 to 6 cm/yr in 1969. From

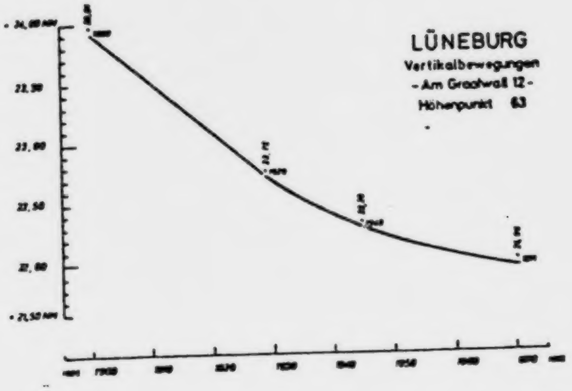


Fig 4-4: Lüneburg 1897-1970 [illegible] [illegible] [illegible] (after [illegible] et al, 1975)

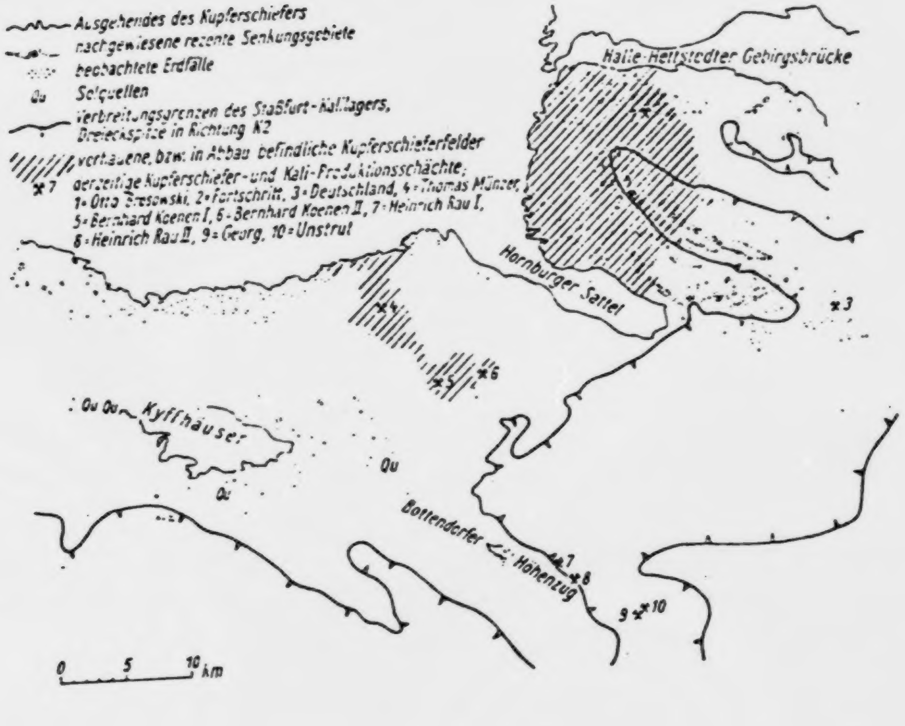

Ausgehendes des Kupferschiefers
nachgewiesene rezente Senkungsgebiete
beobachtete Erdfälle
Qu Solquellen
Verbreitungsgrenzen des Staßfurt-Kalilagers, Dreieckspitze in Richtung K2
verhauene, bzw. in Abbau befindliche Kupferschieferfelder
7 derzeitige Kupferschiefer- und Kali-Produktionsschächte; 1 = Otto Brosowski, 2 = Fortschritt, 3 = Deutschland, 4 = Thomas Münzer, 5 = Bernhard Koenen I, 6 = Bernhard Koenen II, 7 = Heinrich Rau I, 8 = Heinrich Rau II, 9 = Georg, 10 = Unstrut
Halle-Hettstedter Gebirgsbrücke
Hornburger Sattel
Kyffhäuser
Qu
Bottendorfer Höhenzug
1
2
3
4
5
6
7
8
9
10
0
5
10 km

Fig 4-5: Copper shale mining [illegible] [illegible] (Einecke [illegible], 1959)

September 1970 to September 1971, during which period the sinkhole formed, 11 cm/yr of vertical subsidence were recorded.

The writers emphasize that such sinkholes are caused by the collapse of karst cavities in the gypsum above the top of the salt. Water flowing through karstified gypsum may simply flush out sediments accumulated in cavities such as demonstrated on Fig. 4-10.

SCHMIDEK (l.c., p. 838) reports over 40 sinkholes within the city limits of Lüneburg. The last one with the volume of approximately 35 m^3 formed during the year of publication of his report. The writer also reports numerous smaller sinkholes which were caused by leaking sewage lines.

The writer stresses that a brine well collapsed in 1907 after only one half year of brine pumping: these reports clearly classify smaller and larger sinkholes as man-made collapses.

In contrast, DRESCHER et al. (1973) diligently avoid any mention of relationships between the brine pumping operations, localized surface subsidences and the related formation of sinkholes. However, the changeover from wild brining to controlled solution mining in 1961 indicates that the true causes of extensive subsidence damages in downtown Lüneburg were recognized - too late, of course, as natural solutioning processes continue along the pathways created by uncontrolled brine pumping over more than half a century.

4.5 NATURAL SOLUTIONING AFFECTED BY MINING

4.5.1 Geological conditions

Mining operations underneath areas of active natural salt solutioning by groundwater have serious effects when groundwater flows into the mine workings, dissolving salt out of overburden strata. The resulting salt solutions must be pumped out of active mine workings. Sooner or later, the continuing dissolution of salt along the pathways of the inflowing water will force to leave the mine to flooding, see 3.2 for case histories.

In cases of unlimited groundwater supply, the inflow rates tend to increase in time as the pathways are widened by salt solutioning.

In contrast, the discharge of fluids from isolated reservoirs is characterized by decreasing inflow rates as shown in I/4.6.

The possibility of using the development of inflow rates as a criterion in assessing the flooding potential is re-emphasized.

Uncontrollable surface subsidence was experienced in areas where salt solutions were pumped out of operating potash mines for many decades in order to keep the mines operational, see 3.2.

It is stressed with reference to 3.2.4, and 4.2 that natural salt solutioning processes which terminated may be re-activated by mining operations. Caprock offers little resistance to overburden deformation caused by extended underground mining. For this reason, re-activated natural solutioning processes frequently are characterized by rapidly increasing inflow rates.

The following case histories deals with mining underneath Zechstein salt deposits in Germany. The reader is reminded of questionable concepts of natural evaporite solutioning criticized in 4.1. It is re-emphasized that subterranean dissolution of salt rocks does not create karst features such as observed in other evaporites, particularly in thick anhydrite and/or gypsum beds through which groundwater and/or salt solutions are flowing.

The solubility of anhydrite and gypsum is considerably higher in salt solutions than in fresh water; details can be found in BRAITSCH (1962, 1971). These relationships favor the development of linear karst features in buried anhydrite beds which are fractured and percolated by salt solutions.

However, the difference in the solubilities of salt rocks and gypsum/anhydrite, respectively, is tremendous; the dissolution of relatively thick salt beds may require only a few years, while the development of karst features in gypsum/anhydrite requires geological time periods. These facts must be borne in mind in any discussion of karstification in evaporite sequences.

4.5.2 Mansfeld copper mining district, East Germany

4.5.2.1 Historical and geological background

Starting at the outcrops, the copper shale seam at the basis of the Zechstein evaporite sequences has been mined for many centuries in the Mansfeld basin around and underneath the city of Eisleben.

The Zechstein salts are completely dissolved near the outcrops. The anhydrite members of the Zechstein evaporites are severely karstified wherever the salt is partly or completely missing due to solutioning.

The boundary of the Stassfurt potash bed is shown on Fig. 4-16. The basin is open to the E. The mine No. 3 is the Krügershall/Teutschenthal potash mine which suffered a heavy rockburst in 1940, see 2.2.3.

The geology of the Mansfeld basin is characterized by block faulting which caused some difficulties in following the copper shale bed in mining operations.

Numerous shafts had to be sunk to gain access to the copper shale bed in deeper parts of the basin, so the salt thicknesses are well known. Some of the shafts obtained potash production quotas, and some potash was mined.

For more details on the geology of the Mansfeld basin the reader is referred to JUNG (1968, in GIMM, 1968, pp. 478-487) and to LÖFFLER (1962). Apparently, hypotheses regarding the depositional frame of the evaporites changed considerably over the past two decades. JUNG (1968, p. 483) now assumes extensive contemporaneous solutioning of Zechstein salt which resulted in residue and collapse breccia, and in redeposition of dissolved salt in areas of localized surface subsidence caused by continuing block faulting.

The writer also strongly emphasizes the effects of salt solutioning on present groundwater flow patterns. The extracted copper shale seam rarely exceeds 0.3 - 0.4 m in thickness (LÖFFLER, 1962, p. 67); its extraction cannot have any significant effect on surface subsidence and on the regional groundwater regime.

An important fact should be borne in mind: numerous gas outbursts occurred in development entries since 1916 when deeper mine levels were developed (BAAR, 1962).

JUNG (l.c., p. 486) criticizes the development of the mines in the Mansfeld basin; the different development of the adjacent Sangerhausen basin (mines Nos. 4-6 of Fig. 4-16) is stressed: instead of starting the extraction near the outcrops and advancing to greater depths, the extraction sequence was changed to mining first at safe distances from the outcrop where the overburden is impermeable because of the presence of salt.

The writer apparently recognized that it is the presence of salt that makes the overburden impervious; for this reason, any leaching of salt should be prevented until sufficient storage space for the inevitable inflows near the boundaries of the salt strata is developed in safe areas.

Referring to a sudden, catastrophic water inrush in one of the mines of the Mansfeld basin in 1958, the writer (l.c., p. 480) emphasizes that this event demonstrated the need for comprehensive scientific work to protect the miners and the mine workings against surprises of the following type: water rushed into the mines at the rate of approximately 2000 m/min; the inflow occurred in an old mined-out area, destroying inclined travelways and filling the mined-out areas at deeper levels.

Fortunately, sufficient storage space was available in deeper mined-out areas. The sudden water inflow stopped after a few hours when the underground cavity from which the water came had emptied.

The underground cavity had been created by extensive recent salt dissolution in an old mined-out area; at an unexpected and unpredictable time, the continuing dissolution of salt caused the cavity to break through into an open old travelway.

This writer accepted the assignment to investigate the causes of this sudden inrush, and to assess the potential of similar events in the developing Sangerhausen mining district; similar situations were found in the No. 4 mine of Fig. 4-16.

Development inclines had intersected overlying salt beds at various locations. At insufficient distances from the outcrop, groundwater was flowing through the overburden and developed into more or less saturated salt solutions before entering the mine workings. JUNG's (1968) acknowledgement of these findings is appreciated; the extraction sequence was changed as reported above.

4.5.2.2 Conflicting hypotheses on salt solutioning

JUNG (1968), p. 481) holds on to obsolete hypotheses of local facies changes of rocksalt with thicknesses up to 500 m into equivalent anhydrite up to 150 m thick; the writer contradicts his own cited statements regarding extensive contemporaneous salt solutioning which resulted in anhydrite residues.

LÖFFLER (1962, p. 69) attributes these obsolete hypothese to RICHTER (1942; the writer became known as RICHTER-BERNBURG in numerous subsequent publications). LANGBEIN and SEIDEL (1960) and others show thicknesses of up to 80 m of anhydritic solution residue in the area around the city of Eisleben. Needless to say that residue generated by contemporaneous solution consolidated into solid anhydrite upon burial by thick subsequent sediments.

When affected by later karstification, the consolidated anhydritic residue exhibits the same features as primary anhydrite strata. LÖFFLER (l.c., p. 66) considers the anhydritic residues as resulting from dissolution of the Stassfurt potash bed and parts of the underlying Zechstein 2 rocksalt.

Salt solutioning in the Mansfeld basin accelerated considerably some 100 years ago when the copper shale extraction advanced underneath overburden with salt left undissolved. Fig. 4-17 is based on statistics of the amounts and salt contents of mine waters pumped out of the copper shale mines.

JUNG (l.c., p. 485) emphasizes the difference of 18 m^3/min between water attributable to natural recharge of groundwater in salt-free areas of the Mansfeld basin and the actual amount of water pumped as salt solution out of the mines.

The considerable increase around 1892 co-incides with the disappearance of a rather large lake (over 5 x 2 km) located approximately 15 km east of the mines. The writer shows conclusively that the lake emptied into the mine workings. After the lake had emptied, water of the Saale river kept flowing subterraneously into the mines.

In other words, the natural flow of groundwater out of the Mansfeld basin towards the Saale river was reversed; the reversal resulted in the dissolution of large amounts of salt. The writer (l.c., p. 485) calculates the volume of approximately 98 million m^3 of dissolved salt. The areas of salt solutioning and attributable surface subsidences are indicated on Fig. 4-16.

The writer reports surface subsidences of 2m within 10 years above

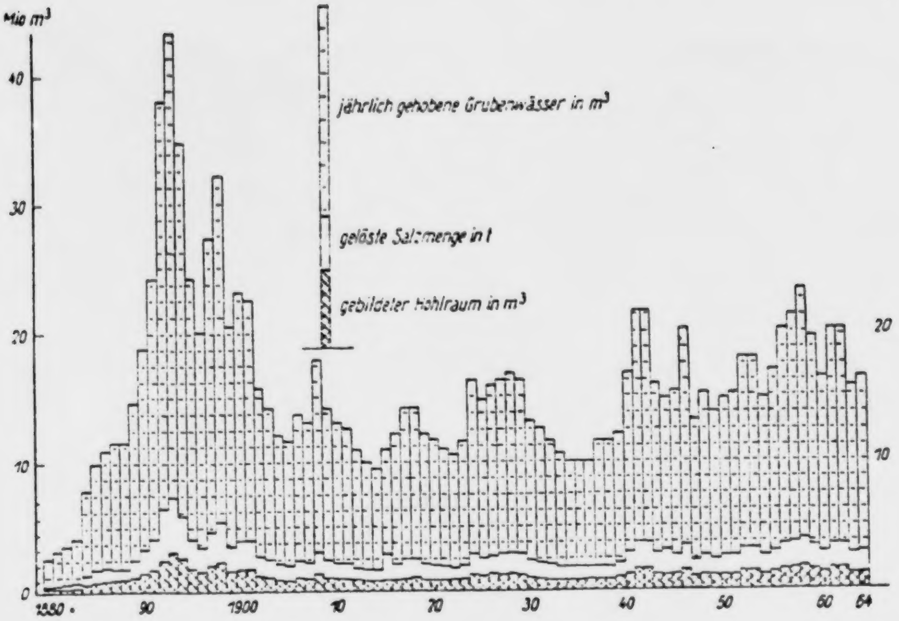


Fig. 4-17: Historical yearly amounts of salt solution
pumped out of mines [illegible]
in [illegible]

mined-out areas with the highest inflow rates; the relationship between the tectonically controlled geology (block faulting) and the general direction of subsiding troughs is considered as evident from Fig. 4-16. Exact data on measured subsidences are not presented.

However, the writer (l.c., pp. 486/487) clearly defines what he considers as the most important result of the investigations obsolete hypotheses calling for natural salt solutioning must be replaced by the hypothesis of potential for water inflow at all boundaries of the various Zechstein salt sequences.

This postulate makes no sense; it is the presence of the lowermost salt sequence that makes the difference as is to be shown later.

The writer (l.c., p. 481) considers the present boundaries of the various Zechstein salt sequences as reasonably well known; the potential of dangerous water inflows and related surface subsidences is considered as predictable within reasonable limits.

Contrasting opinions are held by REUTER et al. (1971, 1977) with specific reference to local cratering in the Mansfeld basin. These writers ignore the reversal of groundwater flow east of the mined-out areas when a lake emptied into the mines. Specifically referring to a remnant of the emptied lake, the Binder Lake, REUTER et al. (1971, p. 15) are critical of "conventional geological methods of documentation" which are believed to increase the quantity, but not the quality of information that must be considered relevant in assessing the causes of localized subsidence and related cratering in the tension zone of surface subsidence troughs.

The writers, like other German writers, emphasize differences between gypsum karst and so-called saline karst assumed to be caused by subterranean dissolution of salt deposits; one of their rather strange statements claims that the karstification of gypsum follows laws of physics and chemistry which make such karstification predictable, while the karstification of salt is considered unpredictable for various reasons. The fact that most German writers assume more or less horizontal surfaces of salt deposits under groundwater attack is also ignored.

On the other hand, the writers (l.c., p. 17) emphasize the significance of vertical fractures along the boundaries of local subsidence troughs; such fractures are believed to provide easy access for meteoric waters to the top of the salt; this, in turn, is believed to cause accelerated dissolution of salt.

The writers do not waste any thought on the proven fact that solution residue which accumulates at the surface of the salt terminates solutioning processes as shown previously; they postulate that surface fractures develop in the known tension zones of subsidence troughs, see Fig. 7-1.

The writers show depth contours of the Binder lake and several cross-sections with observed and assumed surface fractures, and postulate analogies with the characteristics of subsidence troughs caused by coal mining. However, a close examination of their figures show such postulates inconclusive for the following reasons:

(1) The Binder lake, roughly elliptical, has maximum diameters of approximately 100 m and 200 m, respectively.

(2) In August 1969, the water level was at 82 m above MSL (l.c., Fig.2).

(3) According to JUNG (1968, p. 482), the top of the salt was encountered at approximately 150 m below MSL in the so-called Eisleben depression, and at greater depths in other areas of the Mansfeld basin.

It follows from these figures that the Binder lake is underlain by approximately 200 m of Bunter sandstone; this formation is considered as sufficiently competent to bridge spans much larger 100 m, as shown in 2.2. Consequently, subsidences underneath the Binder lake cannot be related to general solutioning at the top of the salt; the groundwater flow followed karst features in the overlying carbonates.

REUTER et al. (1977) present a different hypotheses: "damage to terrain and buildings which occurs at the flanks of subsidences cannot always be explained by the conception of a sinking trough model. Such damage shows features related to slope sliding."

The writers attempt to prove that the reported surface damage near "subsidence areas of chloride-karst...called sinks" are caused "by human activity;" they refer to their 1971 publication (l.c., pp. 16-19) with 3 photographs of surface fractures.

One of the pictures shows a "trench-like cave-in in the western tension zone of the sink"; it is shown in the 1971 publication to prove the development of fractures down to the top of the salt as outlined above.

The writers refer to their 1971 publication, but do not mention the change of their hypothesis to the contrary.

The writers also fail to explain the "human activity" referred to, simply stating (1977, p. 62): "the intense subsidence which has been occurring since 1955 cannot have been caused by mining." This statement shows that the writers continue to ignore the evidence presented in Figs. 4-16 and 4-17 which shows that extensive salt solutioning is due to long-term pumping of salt solutions out of the mines in the Mansfeld basin.

There is, of course, no direct relationship between what is called near-surface sliding and mining underneath the Binder lake which accelerated in 1955. However, the indirect relationship was established beyond doubt by the catastrophic water inflow in 1958.

REUTER et al. (1977, p. 62) report the following details of the "engineering-geological conditions".

"The depression forms a slightly asymmetrical sink with steep and partly fractured flanks. The centre of the sink is now filled with water. Intense subsidence in the Fifties and Sixties disturbed the highway which crosses the sink from north to south. The area has been in the process of subsidence for a long time. A north-south depression about 15 m deep was reported here as early as in 1898."

With reference to Fig. 4-17, it is emphasized here that the formation of the 15 m depression in 1898 co-incides with the rapid increase in the amount of water pumped out of the mines. Although the copper shale seam underneath the depression was not yet mined at that time, any serious doubt can exist as to increased pumping as the cause of surface cratering.

REUTER et al. (1977, p. 62) report that the copper shale seam underneath the 15 m depression was mined in 1909; "between 1910 and 1912 depressions and tension gashes were reported, but the intense subsidence ...since 1955 cannot have been caused by mining."

The writers fail to provide detailed data on the accelerated subsidence since 1955, concentrating on what is considered evidence of "joints and fissures in the tension zone of a sink caused by slope movement." To make this statement understandable, it is necessary to note that the writers refer to the "trench-like cave-in in the western tension zone of the sink", attributing it to slope movement rather than to the depression itself which is also called a sink as quoted above.

In the following quotation (1977, pp. 62/63), the term "sink" is used for the larger depression. At its centre the water was 22 m deep, apparently due to the termination of pumping salt solutions out of the abandoned mines of the Mansfeld basin.

"The slightly asymmetrical sink has steep western and northern flanks. In 1968 various tension gashes opened in the north-western flank. They were filled in 1969. Following a wet spring in 1970, new tension gashes over 50 cm wide and some over 2.50 m deep opened in the northern and western tension zones. At the same time a trench-like cave-in occurred in the western tension zone."

Except for their reference to subsidence in areas of "chloride-karst," the writers give no indication of the "underground leaching processes" referred to; they change their 1971 interpretation of the very same "trench-like cave-in in the western tension zone of the sink" as follows:

"The convex ridges on the western flank of the sink cannot be explained by a sinking-trough model, but such ridges are characteristic for near-surface slope sliding. Moreover, this kind of trench-like cave-ins resembles phenomena observed with sliding in opencast brown-coal (lignite) mines where bed surfaces act as sliding planes."

The writers apparently are not familiar with the phenomena observed in the tension zones of troughs of localized subsidence. Convex ridges are characteristic of tension cracks all around relatively deep local depressions, no matter what causes the localized subsidence. Increasing age and weathering may result in near-surface sliding, particularly in cases where the groundwater level in the depression is raised relative to the surrounding area; this apparently was the case in the area under discussion after the mines were abandoned and left to flooding.

The assumption of a bed surface as a gliding plane for near-surface loess is just an assumption of the type frequently made by writers who are not bothered with the lack of factual evidence to support their assumptions.

However, it is emphasized here that loess at the top of glacial deposits.

Many geologists classify loess as impermeable, see 4.1.

4.5.2.3 Interpretation on the basis of underground observations

The following interpretation is based on this writer's findings in the mine No. 4 of Fig. 4-16 between the mine shaft and the outcrop of the copper shale bed. This area had been mined prior to World War II; at the time of this writer's investigations in 1959, extraction mining was in progress just south of the mine shaft as indicated on Fig. 4-16. This writer strongly recommended to postpone the extraction of this area for the reasons outlined above (after JUNG, 1968).

Evidence of the existence of a large underground cavity created by the dissolution of near-horizontal salt beds above the copper shale seam was established in an inclined ventilation drift along the western edge of the area to be mined north of shaft No. 4 of Fig. 4-16.

The reader is reminded of the geological situation in both the Mansfeld basin and the adjacent Sangerhausen basin: the sedimentary sequences are severely affected by block-faulting; there is a general dip towards the centre of the basins; however, each individual block may have been tilted and displaced similar to what is shown in Figs. I/2-25 and I/2-26.

The strata of any individual block may exhibit near-horizontal bedding and may be encountered at a higher elevation behind a fault although the general dip would suggest a lower elevation.

Such a situation was encountered in the incline along the western edge of the area referred to. The incline followed the copper shale seam to the S and hit a fault behind which the seam could be expected approximately 50 m above its elevation north of the fault. Exploratory drilling revealed the presence of gases near the fault, indicating that at least the deepest salt bed in the overburden had not been removed by previous natural salt solutioning.

The stratigraphic sequence above the copper shale seam is made up of approximately 40 m of anhydrite, up to 15 m of rocksalt followed by another anhydrite bed approximately 60 m thick which is overlain by the Zechstein 2 rocksalt with original thicknesses up to 500 m (Fig. I/2-6).

In situations as encountered in the incline it was standard procedure to take advantage of the first roof rocksalt bed in the following way: a cross-cut from the copper shale seam was driven into the salt bed; then the roadway followed the salt bed until the fault was hit. Depending on the elevation of the copper shale seam at the opposite side of the fault, either an incline or a raise were driven through the fault to the elevation of the seam.

In the case under discussion, this procedure resulted in a virtually horizontal stretch approximately 200 m long in the rocksalt bed above the seam. The elevation of the seam behind the fault turned out to be a few metres above the top of the salt bed, so a short raise was driven to reach the copper shale seam. From that point down to the level of the bottom of shaft No. 4, the slope of the seam was regular, following the general dip.

When the area north of shaft No. 4, was mined inflowing water was handled in the following manner: approximately halfway between the shaft and the outcrop the water was intercepted in a striking drift and pumped to the surface; this water was fresh water as no salt was left in the overburden.

Water seeping into the mine in the area above the level of the bottom of shaft No. 4 was also collected in a striking drift and pumped to the surface through that shaft. These waters contained varying amounts of salt, depending on whether or not salt was dissolved at any specific inflow location in the mining area.

The first intercepting pumping system was shut down for several years during and after World War II. Fresh water was allowed to flow down the ventilation incline; it filled the 200 m horizontal salt stretch and flowed over when it reached the elevation of the copper shale seam south of the fault.

The overlow contained salt dissolved in the near-horizontal 200 m stretch. The continuing replacement of overflowing salt solutions by freshwater resulted in a cavity in the salt bed. The cavity could be inspected in 1959 after the intercepting pumping system had been put back in operation and the remaining salt solutions had been pumped out of the cavity to restore the ventilation system which was interrupted by the water plug in the incline.

The cavity in the salt was approximately 4 m high, resembling the thickness of the salt. At both sides of the 200 m stretch, the cavity extended at least 50 m into the salt. The exact dimensions could not be determined as the cavity was partly filled with salt beds which had separated from the overlying anhydrite and were only partly dissolved. Apparently, some roof salt beds had separated from the anhydrite after the cavity had been emptied.

The overlying anhydrite was found bridging the cavity, apparently behaving like an elastic plate which did not require any additional support along the incline.

No change to the situation was detected over several years of observation; there was no indication of possible failure of the bridging anhydrite bed. Observation props set for that specific purpose did not take on any load.

These observations led to the conclusion that dangerous situations could have developed at other locations, particularly in the Mansfeld basin, wherever the first roof salt had been exposed in mine workings. The dissolution of salt could have taken place over many decades, as shown in Fig. 4-17.

At any unpredictable point in time, large brine-filled cavities such as the one observed could extend into open mine workings or reach dimensions which would result in failure of bridging anhydrite beds.

As a matter of fact, an examination of the mine maps of the area in which the catastrophic 1958 water inrush occurred suggested that indeed a situation similar to that described above had developed. When the breakthrough into the mine workings took place, the inflow rate amounted to an estimated 2000 l/min for some hours. Needless to say that the roadways through which the water rushed to deeper levels were destroyed beyond repair.

Referring to undissolved remnants of the Zechstein 1 rocksalt, JUNG (1968) emphasizes the possibility that large underground cavities filled with water may form in the Zechstein 1 rocksalt. Due to the limited thickness of the Zechstein 1 rocksalt - approximately 4 m in the case history discussed above - such cavities may reach large dimensions before collapsing due to roof failure or before leaching through into travelways kept open for sampling and/or ventilation.

The writer postulates that mining through the Zechstein 1 rocksalt should be avoided - however, exactly that had been practised for decades in situations such as encountered in the described case history.

In fact, the writer fully confirms this writer's findings which is acknowledged.

JUNG (1968) and REUTER et al. (1971, 1977) fail to mention the numerous rockbursts which occurred in the copper shale mines of the Mansfeld basin. It is this writers opinion that the stronger rockbursts were caused by tensile failure of anhydrite beds above cavities in the Zechstein 1 rocksalt when such cavities reached excessive spans.

The collapse of large cavities in the Zechstein 1 rocksalt is also considered as the cause of localized surface subsidences.

As a matter of fact, the seismorgram of the 1940 rockburst above the potash mine No. 3, Fig. 4-16, was registered by a seismograph set up in the Mansfeld basin for the registration of rockbursts above the copper shale mines, see 2.2.4.

CHAPTER 5

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CHAPTER 5

SOLUTIONING IN ROOM-AND-PILLAR POTASH MINES

5.1 Solutioning By Saturated Brines

The headline for this introduction was chosen to emphasize the extremely complex solubility relationships between various potash ores and brines which are saturated with respect to certain components, e.g., NaCl.

Natural solutioning of rocksalt deposits results in solutions which may be saturated with respect to NaCl, but contain only traces of other salts; such solutions must not be considered as saturated when they contact potash salts. As emphasized in I/2.1.1, the complete understanding of the physicochemistry of these relationships must be demanded of geological investigations, especially of investigations involving solutioning processes in potash mines.

It is not possible to deal here in any more detail with the physicochemistry of such solutioning processes. With reference to I/2.2.3, some basic relationships which are important in the following discussions are reemphasized as follows:

(1) NaCl solutions contacting sylvinite tend to develop into NaCl-KCl equilibrium solutions; sylvite is dissolved, halite (rocksalt) crystallizes.

(2) NaCl-KCl solutions contacting carnallite tend to develop into $MgCl_2$-rich equilibrium solutions; such solutions are particularly complex in systems which also contain sulphate ions. Due to the solubility of $MgCl_2$ minerals, large amounts of halite and sylvite may form.

(3) Solutions rich in $MgCl_2$ may develop into solutions rich in $CaCl_2$, e.g., in processes of dolomitization.

(4) Cooling of solutions which ascend in fractures through salt deposits frequently results in crystallization of secondary salts as shown schematically in Figs. I/2-16 and I/2-21.

(5) In cases of high surface temperatures, cooling of solutions which seep through unconsolidated underlying evaporites also may result in crystallization of secondary salt minerals, see Fig. I/2-12.

(6) Solutions and gases may be trapped for unlimited periods of time in salt deposits as shown in Fig. I/2-15; this fact is frequently emphasized throughout this text as proof of the impermeability of undisturbed salt deposits which were buried by subsequent sediments of

certain thickness, see I/3.6.2.

(7) Solutions and gases occluded in secondary salt minerals cannot be drained through boreholes, but may cause heavy outbursts of salt and gas when mine openings come too close, see I/4.5.1 and 2.4.1.3.

The monograph published by BRAITSCH (1962, 1971) should be consulted by readers interested in a more detailed introduction into the special field of solution equilibria of oceanic salt systems. It must be stressed that years of intensive studies are required for an adequate understanding of these extremely complicated relationships.

Criticism of untenable hypotheses promoted by writers who failed to familiarize themselves sufficiently with the subject matter is frequently required: As D'ANS put it in his preface to D'ANS and KUHN (1960, p. 69) in a critical review of publications: once again, the beautiful geophantasy (of writers who deal with mineralogical and petrographical aspects of potash deposits) conflicts with the clear-cut, exact science of physico-chemistry,

Similar criticism is necessary regarding some publications to be dealt with in the following.

5.2 CARNALLITE DISSOLUTION, SOUTH HARZ DISTRICT, GERMANY

5.2.1 Historical data, geology, potash mining methods

At the beginning of this century, the few mines left after the disastrous learning period of German potash mining in the Stassfurt area, see 3.2, faced another difficult situation: the potash mining activities began to shift to areas with flat-lying potash beds. In one of these areas, known as the South Harz district, the Stassfurt potash bed was encountered in much better quality; in some areas it consists of high-grade sylvinite of considerable thickness. At the beginning of the potash mining boom in the district, high-grade orebodies were selected for the location of approximately 33 potash mine shafts; only a few of them fell victim to water problems during shaft sinking; many of the mines are still in operation.

The potash mines at depths from approximately 400 to 1100 m are protected against near-surface groundwater by a rocksalt sequence exceeding 100 m in thickness. Some geological features are shown in Vol. (Figs. 2-6, 2-16, 2-19, 2-20, and 5-10). Results of rock-mechanical investigations are dealt with in I/5.3.2; the significance of Fig. I/5-13A is re-emphasized.

Results of surface subsidence measurements are presented and discussed in 7.2. The need for careful control of floor deformations underneath mined-out areas has been known for many decades; gases may be released from reservoirs underneath the mines, see 3.5.2. Disastrous gas explosions in 1951 demonstrated again the need for effective floor control. Mining methods with intentional roof caving for better floor control are discussed in 8.1.

For more than half a century, mining methods with hydraulic backfilling have been used: refinery waste is piped into mined-out room-and-pillar panels. Leading German theoreticians believed in positive effects of the solidifying refinery waste on the stability of the mine pillars; some still consider hydraulic backfilling as necessary when the potash bed exceeds approximately 5 m in thickness.

In fact, however, hydraulic backfilling of mined-out room-and-pillar panels may result in uncontrollable floor deformations, particularly when hot refinery waste is piped into the mines.

In addition, the well-known solubility relationships between carnallite and brines used in the backfilling operations were ignored; this is the main cause of uncontrolled floor deformations which released huge amounts of gases and brines into the potash mines located in the western part of the district. Gas pressure drives the brines up into the mines; Fig. I/4-21 shows the typical development of brine discharge rates measured in two potash mines near the NW corner of the East German part of the South Harz district.

Prior to any further discussion of the subject matter some historical data are presented as they give the clue to the fact that many publications cannot be considered reliable: many published data on gas and brine occurrences are arbitrarily selected; some are falsified to serve specific purposes pursued during various periods of the potash mining history of the district.

The reason why so many shafts were sunk in the South Harz district are explained by WEAVER (1963): in order to obtain a production quota, it was necessary to show potash ore in situ. Many shafts were sunk for the sole purpose of obtaining a production quota; subsequently, the quota could be transferred to a mine the operational conditions of which were considered superior by the respective company.

Around 1930, 4 competing companies operated 5 potash mines in the district. Many potash shafts had been lost due to "natural causes" beyond the control of the owners. In such a case, the quota remained valid.

A number of operational potash mines had to be maintained in stand-by condition in order to keep the respective quotas which had been transferred to operating mines. Such idle mines were a financial burden because of the continuing maintenance costs. Needless to say that "natural causes" of flooding were quite welcome; the term "flooded, causes unknown" is found frequently in German statistics on potash shafts.

The 4 companies operating in the district kept their own experts on their payrolls to show "natural cause" when an idle potash mine was lost to flooding. The situation changed to the opposite during the 1930's when the military became interested in idle mines; now the same experts had to show idle potash mines and those lost to flooding suitable for military purposes; they succeeded in most cases.

Most of the idle potash mines in the South Harz district were rehabilitated, or were under reconstruction when the end of World War II reversed the situation again: surplus mines leased to the military were no longer of any use to the owners. In addition, the ownership was in question for some years.

These circumstances must be borne in mind when dealing with conflicting reports and statements regarding the causes of gas and brine inflows into the potash mines in the western part of the South Harz district; the rock salt sequence underneath the mines is only 30 - 50 m thick; locally, even smaller thicknesses are encountered. Known gas and brine reservoirs underneath the potash mines make uncontrolled floor deformations extremely dangerous, see 3.5.

Due to increasing thicknesses of the protecting rocksalt towards the E, see Fig. I/2-6, control of floor deformations is less important in the eastern part of the district.

In 1944, as outlined in 7.2.1.1, this writer was assigned to investigate the causes of gas explosions in potash mines of the district; the assignment covered the operating potash mines and those used or being rehabilitated for military purposes. In 1945, the Soviet Military Administration ordered the continuation of these investigations in co-operation with Russian engineers; it was decided not to destroy idle, rehabilitated mines if the mines were suitable for future potash production.

Upon advice by BAUMERT (1946), this decision was overturned regarding the two mines dealt with in the following sections. The contents of the unpublished report can be found in the publication by GIMM and MEYER (1962, pp. 486-489). The 1946 report contrasts sharply to an earlier report (BAUMERT, 1938) related to efforts to lease the two mines to the military. The writer was in charge of the two idle mines and the operating Bischofferode mine, see 5.2.2.

Needless to say that the condemnation of two operational potash mines resulted in controversies. According to the investigations referred to, the idle mines were in no more danger than the operating potash mines. As BAUMERT's (1938) report was checked out carefully by other experts, it is considered reliable; for this reason, the following sections are based on the 1938 report and related reports; the condemnation report (BAUMERT, 1946) which contradicts the former reports cannot be accepted.

After all, it makes little sense to declare idle potash mines suitable for military purposes but not suitable for future potash production.

The controversies continued in publications dealing with the causes of mass accidents in operating potash mines in 1951, see I/4.6.4. and 3.5.2. The data reported by GIMM and MEYER (1962) are those found in the condemnation report (BAUMERT, 1946). The publication of correct data (BAAR, 1957) was suppressed. The correct data and additional information are compiled in another unpublished report (BAAR, 1964a) which is the basis of the following discussions.

All this may be of limited general interest as far as the specific geological conditions of the South Harz district are concerned. However, in view of considerations to dispose refinery waste underground in mined-out areas of other potash mining districts, the following case histories may demonstrate possibilities of solutioning in potash mines by solutions which are saturated with respect to NaCl and/or KCl; uncontrollable floor deformations may occur if and when support pillars are weakened or destroyed by solutioning. Of course, excessive roof deformations may be much more dangerous under different geological conditions.

5.2.2 Dissolution of carnallite in mine entries

Unexpected gas occurences in several potash mines of the South Harz district in 1944/1945 had to be investigated by this writer on behalf of the German National Research Council in co-operation with some of the affected companies. At that time, the reports were classified as confidential; some results were published after disastrous mass accidents in 1951 had shown the need for clarification and publication in order to prevent future disasters (BAAR, 1952b, 1953c, 1954b, 1954e). The publication of the latter report was suppressed, as reported by FULDA (1963, references 1 and 2). A comprehensive summary, accepted for publication in Bergakademie (BAAR, 1957), never appeared; however, some of its contents can be found in GIMM and MEYER (1962).

The latter publication is to be corrected in many regards. FULDA (1963) apparently intends to correct the criticized publications, fully confirming this writer's findings during the 1940's and documenting subsequent cases of carnallite leaching. Expensive maintenance work in mine entry systems became necessary. The writer leaves no doubt of the danger caused by continuing disregard of the solubility relationships between backfill brines which are not saturated with respect to $MgCl_2$, and carnallite layers left unextracted in or underneath sylvinite pillars.

The known solution equilibria of the respective salt rocks make such solutioning processes predictable; as a matter of fact, some of the cases reported by FULDA (1963) were repeatedly predicted in this writer's unpublished report referred to above, and in publications based on investigations in the Bischofferode mine (BAAR, 1944, 1945). One case history of carnallite dissolution in this mine is documented by BAAR (1958); it took place from 1950 to 1953 and resulted in the particularly dangerous release of gases with high H_2S contents.

At the time when this writer's reports were compiled, analytical data on the actual composition of backfill brines were not available. For this reason the data published by FULDA (1963) are appreciated. Unless indicated otherwise, the following tables are those published by the latter writer.

Table 5-I is of particular interest. The brine samples 1-3 were taken in an access entry to a mined-out sylvinite panel; the wall to retain the waste in the panel was erected in carnallite, as documented in detail in the reference publication.

For those readers who are not familiar with hydraulic backfill operations in German potash mines it may be mentioned that the refinery waste is piped as slurry from the surface to the highest elevation in any mined-out room or panel. The composition of the brines used in such operations may change, depending on the composition of the ore processed at any specific time. The brines are collected in underground reservoirs and

TABLE 5-I

Analyses of backfill brines, Bischofferode potash mine

Composition in g/l; see text for explanation of brine samples.

Number	$MgCl_2$	KCl	NaCl	MgSO4	H_2O	Remarks
1	86	102	175	18	866	
2	92	106	164	23	867	
3	255	57	46	48	884	
4	25	119	251	3	n.a.	questionable, see text
5	95	85	169	25	n.a.	
6	103	102	156	22	n.a.	
7	111	97	150	22	n.a.	
8	68	89	202	15	n.a.	
9	14	70	257	29	n.a.	error in GIMM (1968, p. 471: 10 instead of 70 g/l KCl)

pumped back to surface reservoirs.

Analysis 1 of Table 5-I gives the average composition of the brines used at the time of the investigation. The backfill operations had to be halted after only 3 days because the brines which drained off the solidifying waste dissolved carnallite around the retaining wall.

Analysis 2 indicates the composition of brines which drained directly through the retaining wall; the analysis shows no significant changes.

Analysis 3 gives the composition of brines which drained through the residue of dissolved carnallite around the retaining wall. It is emphasized that only a short period of time was required to produce the evident changes in the composition of the brine; in brines which would no longer dissolve carnallite approximately 320 g/l $MgCl_2$ must be present under the given conditions.

Analyses 4-7 (from GIMM and MEYER, 1962, Table 1) indicate the composition of what the writers call typical backfill brines at the same mine. The brine samples were taken underground. The analyses indicate various degrees of carnallite solutioning. 4 is questionable as 8 gives the average brine composition in surface reservoirs; $MgCl_2$, the most soluble component, cannot decrease.

GIMM (1968, p. 455), citing the analyses 4-6 and 8, emphasizes the solubility of carnallite in backfill brines with the composition of 8; therefore, the $MgCl_2$ content of backfill brines used in carnallite areas should be as high as possible; retaining walls should be built in rocksalt or sylvinite; under no circumstances should underground brine reservoirs be located in carnallite. Typically, previous publications which proved these relationships (BAAR, 1958; FULDA, 1963) are not mentioned.

FULDA (l.c., p. 449) reports another observation which clearly shows the solubility of carnallite in solutions with the composition of analysis 1: some of the brines which drained off the backfill entered the adjacent parallel room, flowing on the surface of carnallite exposed in the floor; within 3 days a ditch 1 m deep and 0.8 m wide was dissolved in the carnallite.

The retaining wall was repaired, and the backfill operations were resumed, causing more serious damage due to carnallite dissolution. 40 m^3 of waste broke through into the main entry and interrupted the main haulage system, see 7.2.1.4 for similar incidents. It was decided to postpone the backfill operations until the entry was no longer needed as haulage entry.

TABLE 5-II
Changes to the composition of backfill brines, Bischofferode potash mine
Composition in g/l of (1) average backfilling brine at the time of investigation, (2) backfilling brine after dissolution of carnallite.

	$MgCl_2$	KCl	NaCl	$MgSO_4$
(1)	68	89	202	15
(2)	218	67	68	40
Difference	+150	-22	-134	+25

The analyses of Table 5-II indicate the causes of severe damage to another haulage way in the same potash mine. The writer, referring to this writer's (BAAR, 1958) report on a similar case which occurred from 1950 to 1953, provides a comprehensive documentation by photographs, location maps, and sections along the damaged main haulage way. According to the mine plan (l.c., p. 450), damage by carnallite dissolution occurred over at least 3 km length; thicknesses up to 5 m of the underlying carnallite were found in boreholes. The carnallite was dissolved only at one side of the haulage way as a parallel opening was used as an underground brine reservoir. Damage was particularly severe over the length of 200 m of the main haulage way.

The writer provides analyses of the carnallite residue, and of precipitates in brine reservoirs along the main haulage way; the latter precipitates, characterized by relatively high contents of NaCl and KCl, were apparently caused by cooling when brines drained out of backfilled mined-out areas. Crystallization of halite and sylvite is to be expected when solutions rich in $MgCl_2$ are cooled after leaving the backfill areas. The writer theorizes (l.c., p. 452) that the crystallization of halite and sylvite may have reduced the damage due to carnallite dissolution. Showing 6 photographs of artificial support of the roof of the entry, the writer re-emphasizes the seriousness of the damage to the important haulage way, and the costly repair that became necessary.

The writer reports on several other cases of carnallite leaching in other potash mines of the South Harz district, presenting brine analyses and documentation of the mining situations considered to have caused the dissolution of carnallite by backfill brines. The interested reader is referred to the reference publication.

5.3 NEUBLEICHERODE POTASH MINE - A TEXTBOOK EXAMPLE OF ERRORS

5.3.1 Geology, mining methods

The fate of the Neubleicherode potash mine can be considered as a textbook example of consequential errors and misconceptions. Eventually, the mine was left to flooding. The mine is one of the two rehabilitated potash mines condemned and left to flooding as reported in 5.2.1.

The decision to leave this mine to flooding appears particularly strange. The flooded mine workings are surrounded by a large safety pillar, preventing the development of the adjacent Bischofferode mine as mined-out areas of the latter mine are located just west and north of the flooded mine. The operating mine cannot be developed towards the north because of the vicinity of the boundary of the salt deposit. For these reasons the condemnation of the Neubleicherode mine was the subject of most of the controversies mentioned in 5.2.1.

The mine, operating since 1912 at the depth of 650 m below surface, was among the first potash mines to introduce hydraulic backfilling in 1913; within less than 4 years, the backfill operations caused large-scale floor deformations which released gases and brines from the known reservoirs underneath the mine. Fig. I/4-21, curve 1, shows the development of the brine inflow rates. The gases which forced the brines up into the mine were particularly dangerous because of high H_2S contents.

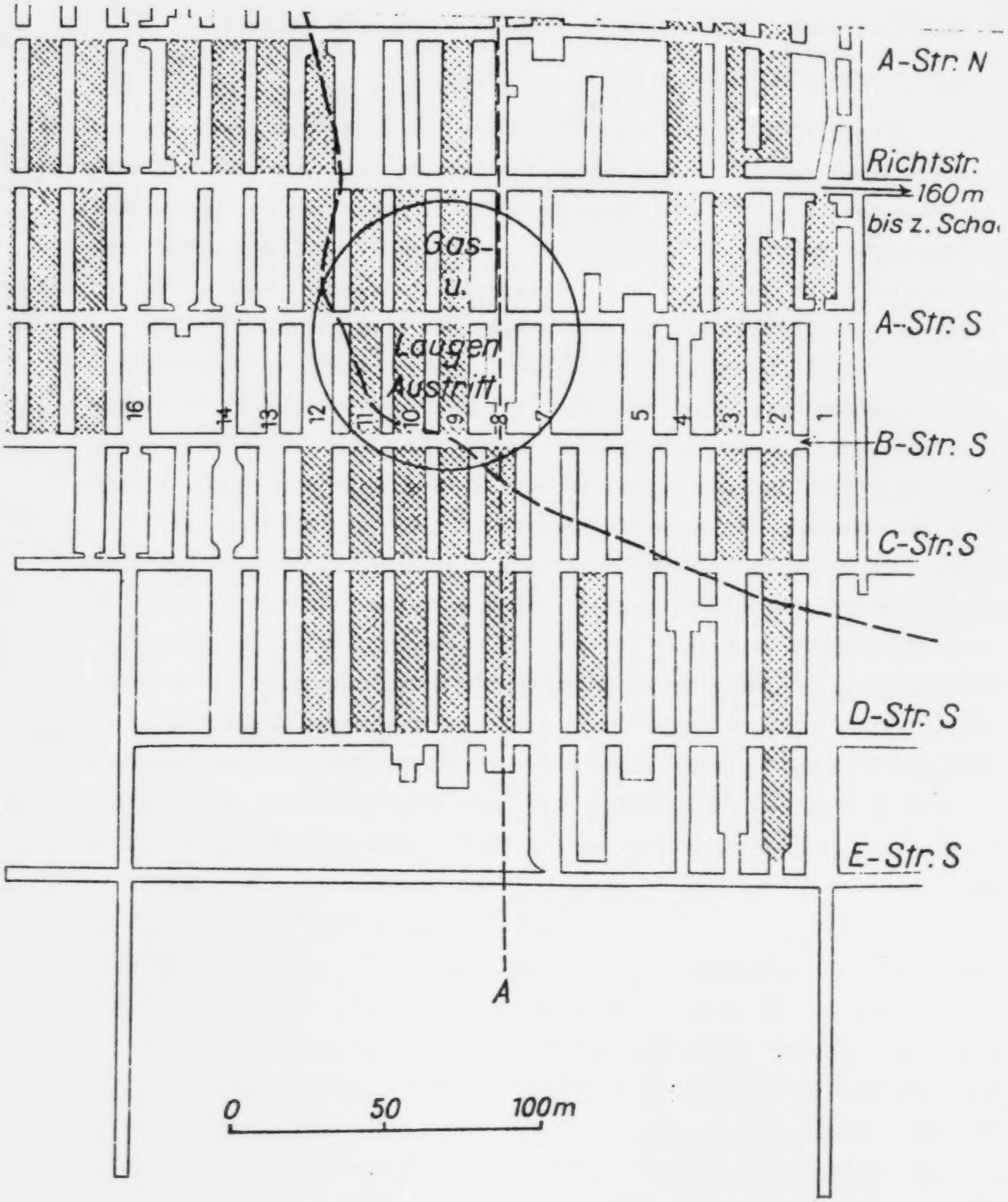
Fig. 5-1 shows the mined-out area in which apparently extensive solutioning of carnallite by backfill brines resulted in uncontrollable floor deformations in 1917. Carnallite of unknown thickness was present underneath the extracted sylvinite; west and south of the carnallite boundary shown on the mine map the extracted potash bed consisted of anhydritic sylvinite which could not be dissolved by the backfill brines.

Near the carnallite boundary, the extracted sylvinite was up to 10 m thick. The design width of the rooms was 10 m, and the pillars were supposed to be 5 m wide; however, the map indicates that some pillars were only 3-4 m wide. The map also indicates rather irregular extraction patterns; the rooms 9 - 11 in the circled area were already in the process of being backfilled, while extraction was still in progress to the west and to the east where large pillars provided better overburden support and control of floor deformations.

Due to these circumstances the source of gases and NaCl brines could not be located exactly. The outflow of brines was first noticed in February 1917 when the brines drained out of the rooms 9 - 11 in the B entry of Fig. 5-1. These rooms are located in a local syncline with the axis dipping gently southward; apparently, the syncline reflects the loss in volume of original carnallite upon conversion into sylvinite, as shown schematically in Fig. I/2-19. The dissolution of the remaining carnallite in rooms 9 - 11 resulted in deformations similar to those shown in detail in I/2.4.

The gases released from the tapped reservoir consisted mainly of CH_4; one miner was killed by an explosion set off in the exhaust airway. H_2S contents of 0.5 - 1.1 Vol% made the gases extremely dangerous.

The brines which drained out of rooms 9-11 soon developed into solutions without $MgCl_2$, containing 23.74% NaCl, 4.92% KCl, and 4.48% $MgSO_4$ (GIMM and PFORR, 1962, p. 486). Apparently, there was no carnallite left that could be dissolved. It must be stressed that the composition of the


A-Str. N
Richtstr.
160m
bis z. Scha
Gas-
u.
Laugen
Austritt
A-Str. S
16
14
13
12
11
10
9
8
7
5
4
3
2
1
B-Str. S
C-Str. S
D-Str. S
E-Str. S
A
0
50
100m

brines used for backfill was not checked regularly; possibly, the carnallite dissolution began long before the consequences were noticed.

5.3.2 Conflicting reports on inflow rates

GIMM and MEYER (1962, p. 486) report the following development of the inflow rates: at the beginning of the inflow, the rate was approximately 60 l/min, see Fig. I/4-21, curve 1; however, since the beginning of the inflow is unknown, the figure appears questionable. There are no reports of rockbursts which could have resulted in an initial inflow rate of that order; for this reason it is more likely that the reported inflow rate developed over a longer period of time, perhaps over several months.

According to the writers, the inflow rate increased to 135 l/min on July 16, 1917; after a temporary decrease the inflow rate increased to 140 - 160 l/min between August 16, 1917, and January 17, 1918. The reported maximum inflow rate decreased to 120 - 135 l/min in mid-1919, and to 15 - 20 l/min in 1924. The writers claim that no reliable data are available for the following years because the inflow area was no longer accessible.

These data cannot be reconciled with data researched by other writers. In the first place, another version of the above report must be corrected; GIMM (1968, p. 473) reports heavy floor deformations between the entries A and B of Fig. 5-1 in February 1917; these deformations, apparently caused by lateral creep deformations, are attributed to an increase in volume of the floor carnallite due to moisterizing, whatever that may mean. The facts, of course, are contrary; even water adsorbed from moist air causes the carnallite to disintegrate into residue, mainly sylvite, and solution rich in $MgCl_2$. The solutions are easily squeezed out of the residue if and when pressure is exerted; therefore, floor heave cannot occur. However, the residue has only 50% of the volume of the original carnallite as shown in Fig. I/2-19.

The writer (l.c., p. 473) corrects the above-reported maximum flow rate to approximately 600 l/min on August 25, 1917.

STOLLE (1958, pp. 26/27) has the inflow rates varying between 65 and several hundred l/min, decreasing slowly to complete termination. The writer notes several inflows at other locations; these inflow rates were small.

This writer's search of all files, including those of the mine safety authority, confirmed the reported sudden increases in inflow due to continuing floor deformations; apparently, the pathways of the brines widened when such deformations took place, sending the inflow rate up as shown in Fig. I/4-21. As gas pressure was the driving force, the inflow rate decreased after each sudden increase as shown in Figs. I /4-17 to I /4-20. The last observed deformations on August 21, 1917, sent the inflow rate to the maximum of 617 l/min; within one week the inflow rate dropped to 233 l/min; it continued to decrease according to the gas laws which govern the inflow rates.

These relationships were not recognized at the time of the events. According to hypotheses still held by GIMM (l.c., pp. 468-472, with reference to MEYER, 1966), the inflowing water originated in the outcrop area at some distance to the north and became saturated with respect to NaCl on its way to the inflow area; similar observations had been made in the Stassfurt area, see 3.2, and elsewhere, so the mine management panicked and began to evacuate the mine when the inflow rate reached its maximum.

The unexpected decrease of the inflow rates made it possible to continue the mining operations at some distance from the inflow area. However, those responsible for the extraction methods felt not motivated to improve the pillar dimensions, and to pay attention to carnallite in the floor. Consequently, another gas and brine inflow occurred in 1926, this time at the distance of 700 m from the mine shaft, while the 1917 inflow occurred at the distance of 250 m.

5.3.3 Dangerous extraction methods continued

GIMM and MEYER (l.c., pp. 486/487) and GIMM (1968, p. 474) report some interesting details of the extraction methods which caused the 1926 inflow. The brine analysis, 9 of Table 5-I, shows $MgCl_2$ in solution, indicating continuing carnallite dissolution in contrast to the 1917 inflow. GIMM (1968, p. 471), referring to the analysis published by GIMM and MEYER (1962, p. 487), reports only 10 g/l KCl instead of the listed 70 g/l. It is suspected that the correct KCl content was changed to show KCl contents as observed on occasion of other brine inflows from the floor of potash mines in the district, see Table 5-III. KCl contents of only 10 g/l are not possible in brines which dissolved carnallite or sylvinite and are not saturated with respect to $MgCl_2$ and $CaCl_2$. According to the writers the geological situation was very similar to the 1917 situation; the 1926 inflow also took place in a local syncline.

TABLE 5-III

Analyses (g/l) of brines from floor strata (after GIMM, 1968, p. 471) Western part of the South Harz potash mining district; samples taken before the brines contacted carnallite.

Number	Mine	Year	$MgCl_2$	KCl	NaCl	$MgSO_4$	$CaSO_4$
1	RE	1914	3.6	11.2	302.6	4.8	3.9
2	NE	1926	14	10.0x)	257	29	4
3	Kö -Hi	1938	10	10	294	2	4.5
4	Kö-Hi	1957	5.9	29xx)	298	3	4.1

x) Correct value 70 g/l, some sylvite dissolved

xx) Sylvite dissolved, see 5.5.

RE = Reinhardtsbrun, NE = Neubleicherode,

Kö-Hi = Königshall-Hindenburg

The extraction method had been changed to extraction in slices, similar to the method which caused the 1901 rockburst, see 2.2.1; each slice was backfilled prior to the extraction of the next one. The backfill brines collected in a mined-out room in the deepest area of the local syncline with carnallite underneath the extracted sylvinite. The extraction and backfill methods made the detection of brine inflows by analysis of the brines used in backfill operations extremely difficult. Regular analyses of the backfill brines were not made anyway.

The emanation of gases from the floor was detected early in 1926 when gas bubbled up in the brine reservoir. The reports on subsequent events differ considerably. GIMM (1968, p. 474) eliminates some apparent errors in an earlier publication (GIMM and MEYER, 1962): the brine reservoir was backfilled when the bubbling gas was noticed. Shortly thereafter, gases were noticed in the adjacent room; the gases came from underneath the blasted sylvinite ore, the source could not be pinpointed. The floor became wet, but the inflow could not be seen. The inflow of brine became visible in another adjacent room when a fracture along the center line widened to 10 cm within a few days. The room could be inspected until 1928 when the brine level rose above the floor; the inflow rate was 24-50 l/min.

The writer admits the possibility of greater inflow rates because of extremely severe floor heave and spalling off the pillars; the explanation of these deformations is given by GIMM and PFORR (1962, p. 486) as follows: at the end of 1926 it was planned to extract the pillars between the rooms in the affected panel; the extreme floor heave was considered as a consequence of the overburden load on the pillars. However, this plan could not be completed due to the abandonment of the mine in 1927/1928.

5.3.4 Mine rehabilitated, left to flooding

GIMM (1968, p. 474) assumes that carnallite dissolution underneath the pillars contributed to the floor deformations which released the brines and gases; however, in contrast to the above data, the writer reports that the production was terminated in 1932. On page 437, the writer has 1917 as the year of termination of mining.

In view of these and other apparent errors, other data published by the two writers referred to can hardly be considered reliable, unless confirmed by other writers. The inflow rates from 1926 to 1928 were 23 - 40 l/min according to STOLLE (1958, p. 27); when the brines rose in the mine shaft, the inflow rate was calculated as 0.3 l/min. The writer attributes the latter rate to the increasing hydrostatic head in the shaft which held back the brines in the reservoirs underneath the mine workings.

It is emphasized that such calculations are meaningless; increasing hydrostatic heads may force brines back into depressurized reservoirs, and certainly result in volume loss of air/gas pockets in the mine workings, see 5.4.3.

GIMM and MEYER (1962, p. 487) report on attempts from 1939 until 1942 to seal the flooded mined-out areas against the mine shaft;however, the seals could not prevent the final flooding of the mine shaft from the mine workings. This report is incorrect (BAAR, 1964a, p. 44): due to neglect of shaft maintenance since 1928, considerable groundwater inflow resulted in leaching of carnallite near the shaft, and in the access entries to the mine workings. The shaft lining was torn apart; it was reconstructed when the company leased the mine to the military. As a matter of fact, similar damage occurred in numerous other idle potash mines with carnallite at the bottom of the mine shafts. The damage and the status of reconstruction of shaft linings had to be assessed after World War II. As reported in 5.2.1, this writer was on the assessment team to prepare the decision whether or not potash mines used by the military were to be re-activated as potash mines.

Maintenance of the Neubleicherode shaft was again neglected since May 1945; inflowing groundwater was not pumped to the surface, but caused more carnallite leaching near the shaft, and around the seals against the mine workings. There are ample reasons to assume that these groundwater inflows caused the final flooding of the mine. However, the possibility that backfill brines from the adjacent Bischofferode mine migrated underneath the salt to the flooded mine cannot be excluded. Such migration must be assumed by writers who postulate that groundwater from the outcrops can migrate downdip underneath the potash mines. BAUMERT (1955) still held that position, although it appears difficult to explain the presence of huge amounts of gases underneath potash mines if the floor strata are assumed to have hydraulic connections to the outcrop area.

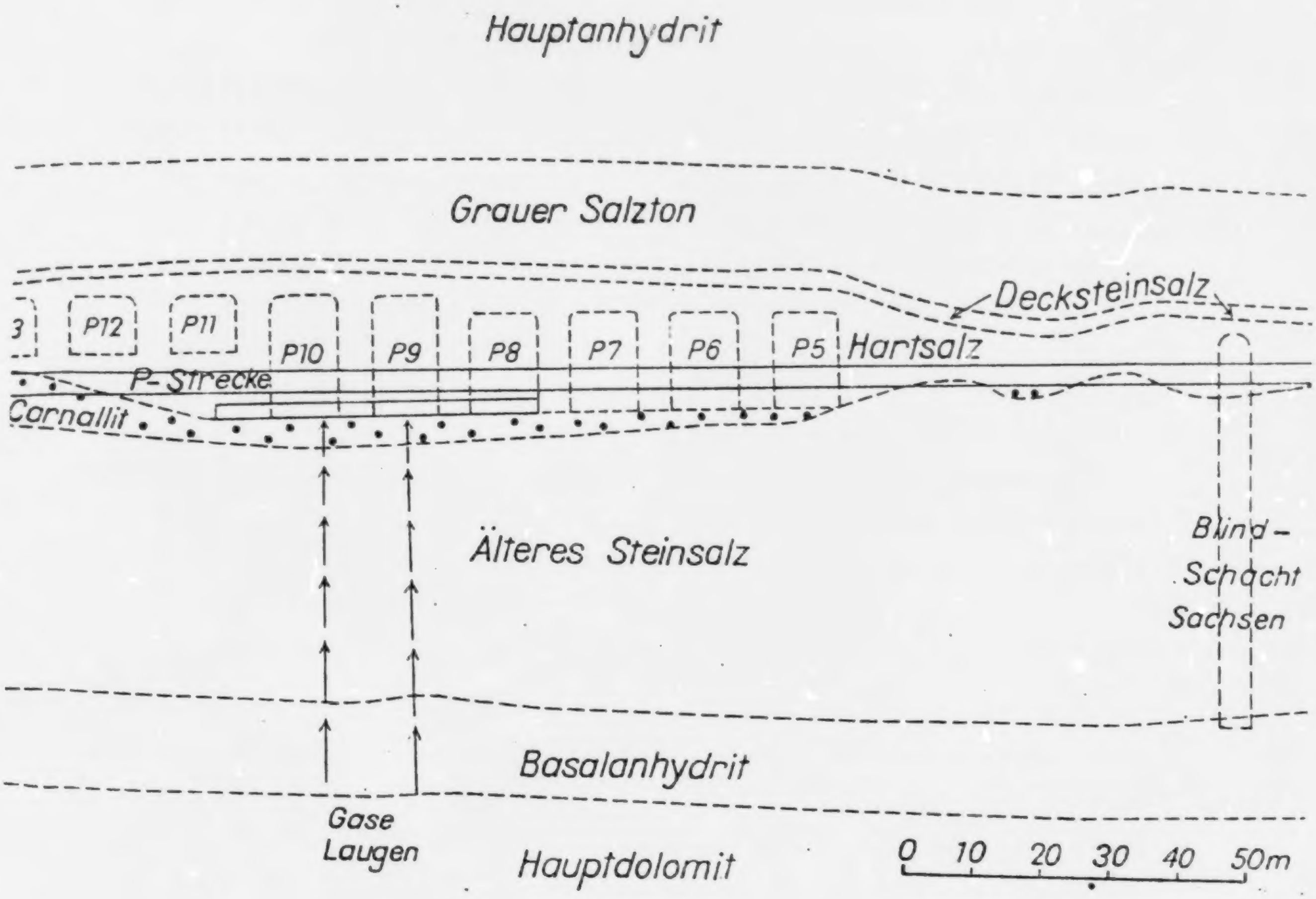
5.4 BERNTERODE POTASH MINE

5.4.1 Geology, extraction methods

This case history has some peculiar aspects; it is summarized as follows (after BAAR, 1964a, pp. 45-48): the mine is located near the south-western solutioned edge of the salt deposit. The two mine shafts were sunk in a local syncline; the Stassfurt potash bed was barren, so a horizontal haulage way had to be driven towards the SE; it hit the basis of the 50-m rocksalt underneath the potash bed at some distance from the main shafts; at this location, an intermediate shaft connected the extraction level with the haulage way, see Fig. 5-2.

The existence of isolated fracture systems underneath the 50-m rock salt was known at least since 1922 when a gas-brine inflow occurred in the haulage way. Within one week, the brine inflow rate decreased from 81 l/min to 0.6 l/min as is to be expected from the relationships shown in Figs. I/4-15 and I/4-17/18. With time the inflow ceased completely.

The brine analysed as follows (g/l): $MgCl_2$ 27, KCl 10, NaCl 254, $CaSO_4$ 2, $CaCl_2$ 26 (see also GIMM (1968, p. 471); GIMM and MEYER (1962, p.487) are listing 27 g/l $MgSO_4$ instead of $MgCl_2$; this is an apparent error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as $MgSO_4$ cannot exist in solutions which contain $CaCl_2$.

The intermediate shaft referred to above connected the main haulage way to an isolated sylvinite panel with approximate dimensions of 150 x 150 m. The panel was surrounded by virgin ground. The extracted sylvinite was up to 16 m thick and underlain by carnallite. Room-and-pillar widths were 10 m and 5 m, respectively, see Fig. 5-2.

The sylvinite bed was extracted in slices; each slice was backfilled as described in 5.3.3. However, the backfill material (refinery waste) was not piped, but transported in cars; the cars were cleaned with brine. The brine collected in the central area of the mined-out panel where it was kept for continuing use. It dissolved carnallite underneath the pillars in the mined-out area.

The dissolution of carnallite resulted in floor deformations, and in brine inflow through the 50-m rocksalt sequence underneath the panel. The inflow probably began in 1927 when the smell of H_2S gases was noticed.

5.4.2 Misleading publications on inflows

In 1928, the brine level in the mined-out panel began to rise. In 1934, when the company began negotiations with the military, the inflow rate of 17.5 l/min was calculated from the measured rise of the brine level. In 1938, the brines began to overflow into the intermediate shaft; the exact determination of the inflow rate of 17 l/min became possible. Changes to the inflow rate are not repoted; this indicates that a rather large volume of gases forced the brines up into the mined-out panel.

At this point, misleading publications are to be corrected: STOLLE (1958, p. 27) and GIMM and MEYER (1962, p. 487) report that the brine inflow occurred in the haulage way between the intermediate shaft and the main shafts in an area which had not been extracted. GIMM (1968, p. 474) corrects this report, apparently acknowledging the data compiled by this writer (BAAR, 1954e, 1964a); however, disregarding the fact that hydraulic backfilling was never used in this mine, the writer reports that backfill brines, mixing with the inflowing solutions, prevented exact analyses until 1938, at which time such mixing was eliminated.

This report makes no sense as the rooms were backfilled slice by slice, so inspection of the backfilled rooms was not possible; brine samples could be taken only in the panel haulage way which was kept open for ventilation. The haulage way was inspected during the company's negotiations with the military; the official report quoted by this writer (BAAR, 1964a, p. 46), leaves no doubt of the damage to pillars due to carnallite dissolution; horizontal voids up to 60 cm wide demonstrated that the pillars were settling onto solution residue of carnallite. The report states that nearly all pillars in the mined-out panel were destroyed as a result of carnallite dissolution by NaCl brines which rose through the 50-m rocksalt sequence underneath the panel.

TABLE 5-IV

Brine analyses (g/l), Bernterode potash mine

YEAR	$MgCl_2$	KCl	NaCl	$MgSO_4$	$CaSO_4$
1932	118	97	140	10	-
1933	116	94	145	11	-
1934	147	89	130	13	-
1938	96	94	175	4	-
1939	47	47	238	-	3

The brine analysis compiled in Table 5-IV provide proof of extensive dissolution of carnallite in the mined-out panel; the $MgCl_2$ content of the stagnant brines increased; it decreased rapidly when the brines began overflowing in 1938. Apparently, most of the carnallite was already dissolved.

BAUMERT (1938) agrees with the cited report with respect to the origin of the brines and gases, but disagrees with the conclusion that the collapse of the mined-out panel could result in increasing inflow rates; his arguments are unquestionable. The principal argument is that the 100-m rock salt sequence above the mine provides for safe protection against groundwater inflow; the panel dimensions are only 150 x 150 m.

However, the writer changed his argumentation several times, apparently for the reasons outlined in 5.2.1; GIMM and MEYER (1962) report the 1946 version, attributing the flooding of the mine to another case of carnallite solutioning which, according to the writers, began in 1938. This case was investigated by JUNGHANS (1953). Again, a number of publications (BAUMERT, 1953, 1955; STOLLE, 1958, p. 27; GIMM and MEYER, 1962, pp. 487-489; GIMM, 1968) are to be corrected; the true case history is summarized as follows (after BAAR, 1964a, pp. 37-39).

5.4.3 Extensive carnallite dissolution since 1933

Shortly after the mine was declared idle, another brine inflow began in a different area of the mine in 1933. Two isolated rooms had been mined in an area known for the partial dissolution of the protecting 100-m roof salt sequence by groundwater. The immediate roof of one of the rooms collapsed; the inflow came out of the roof shale at the rate of 6 l/min. Analysis are listed in Table 5-V.

TABLE 5-V
Brine analyses (g/l) and inflow rates (l/min)
Bernterode potash mine; roof failure in two isolated rooms.

Year	$MgCl_2$	KCl	NaCl	$MgSO_4$	$CaSO_4$	Inflow rate
1933	-	13	304	6	-	6
1938, May	3	-	311	-	7	7.5
1938, Oct.	7	2	305	5	5	7.8

The floor of the two rooms consisted of carnallite of unknown thickness. The inflow was ignored. Due to carnallite dissolution underneath the pillar between the two rooms, a horizontal void 3-6 cm wide in the sylvinite pillar could be seen in 1937. Apparently, the floor portion of the pillar was settling onto residue of carnallite dissolution as described above. However, there was a significant difference: the inflowing brine was not accompanied by gases.

Table 5-V indicates a slight increase in the inflow rate in 1938. However, nothing was done to prevent further carnallite solutioning. In 1951, a horizontal bed separation void 40 cm wide was observed in the access entry to the two collapsed rooms.

JUNGHANS (1953, p. 28) interprets the void as indicative of a stress arch across cavities dissolved in carnallite; the inflow rate is reported as less than 8 l/min.

BAUMERT and SPACKELER (1957, p. 501), while in agreement with the stress arch hypothesis, report increased inflow rates at other locations; the writers theorize that water from underneath the floor rocksalt sequence may have been forced up into the mine.

GIMM and MEYER (1962, pp. 487-489) report that the inflow began in 1938, the inflow rate remaining constant at 8 l/min for some time. Referring to the bed separation void in the pillar the writers theorize that roof collapses caused the initial inflow, the brines dissolving carnallite in the floor and causing additional inflow from floor strata. According to these writers, the inflow rate increased to 40 l/min in 1945, and increased further over the following years. In 1952 the mine was left to flooding.

However, the writers also cite STOLLE (1958), reporting the total final inflow rate of only 0.45 l/min calculated from measurements of the rising water level in the main shaft. In fact, there were two main shafts - however, the following point is stressed here regarding the extremely small reported inflow rate which cannot be reconciled with earlier reports: measurements of water levels in the mine shafts which are in the process of flooding must not be used in calculating inflow rates, unless the following relationships are adequately considered:

(1) Needless to say that the increasing hydrostatic head of the water columns in the mine shafts causes groundwater inflows into the mine workings to decrease. However, the hydrostatic head in the mine shafts cannot be determined with sufficient accuracy unless the amount of fresh water flowing into the mine shafts above the water level is known; in cases where such inflows are relatively high in comparison with underground inflows, the entire water column may consist of freshwater with specific gravities next to 1. However, if saturated $MgCl_2$ solutions rising from the mine workings build up a brine column in a mine shaft, its specific gravity may exceed 1.4; in reality, the actual gravity to be used in calculations of the hydrostatic head will be somewhere between these two extremes.

(2) The increasing hydrostatic head in the mine shafts forces increasing amounts of brines back into isolated underground reservoirs from which they originated, depending on the gas pressures left in individual reservoirs/fracture zones, as shown in I/4.6.2, particularly Fig. I/4-18.

(3) In the case under discussion, most open mine workings were located above the level of the highest connection to the mine shafts; when the waters/brines reached the latter level, air could no longer escape through the mine shafts. Unless the volume of trapped air is known, it is not possible to calculate the volume of brine flowing into air-filled cavities; the volume of the trapped air decreases as the hydrostatic head builds up

in the mine shafts.

For these reasons, the reported inflow rate of 0.45 l/min is not only meaningless, but misleading when used in guessing the inflow rates which led to the decision to leave the mine to flooding in 1952.

The discussed contradictory reports on the effects of carnallite dissolution are topped by BAUMERT (1955, p. 731): the writer claims that cosmic forces, specifically the sunspot activity, caused the 1938 brine inflow. In fact, it began in 1933, see Table 5-V. The German potash industry disregarding the numerous lessons taught over more than a century by gas disasters and mine floodings, failed to come to grips with the problems posed by solutioning in conventional potash mines, particularly in cases involving carnallite dissolution; undoubtedly, the criticized misleading publications and reports are to be blamed as they resulted in the condemnation of at least two operational mines.

5.5 SOLUTIONING OF SYLVITE IN ROOM-AND-PILLAR MINES

5.5.1 Physico-chemical relationships

In backfill operations as described in the preceding text refinery waste is piped as slurry into mined-out rooms. Dissolution of sylvite in backfill brines cannot take place for the following reasons: the ground sylvinite ore is dissolved in water at temperatures slightly exceeding 100°C. Due to the known solution equilibria the sylvite is dissolved quickly at such temperatures; rocksalt and other components are not completely dissolved and represent what is called refinery waste.

Upon cooling of the solution obtained in the process, sylvite crystallizes out of the solution, while other components, particularly NaCl, remain in solution. Frequently, the waste is piped immediately into mined-out areas. The brines used in the backfill operations are handled in a closed circuit, being collected in underground reservoirs and pumped to surface reservoirs for use as required. When mixed with hot refinery waste to form a slurry, the brines do not dissolve the waste. However, the pipelines to backfill areas frequently are many kilometres long; cooling of the slurry cannot be prevented; it results in crystallization processes in the pipelines.

In order to keep the pipelines operational, fresh water is used to dissolve precipitates. Needless to say that excessive watering of the pipelines results in solutioning processes underground; frequently, sylvinite pillars are destroyed in this way. Some case histories are described by BAAR (1953c). GIMM (1968, pp. 454/455) is definitely justified in postulating tight control of the watering of backfill pipelines; however, the writer appears unaware of standard procedures followed for decades in backfill operations: the pipelines were watered extensively before and after any backfilling shift. Excessive watering in combination with underdesign of sylvinite pillars and temperature increase resulted in most of the problems experienced for decades in potash mines in the South Harz district of Germany; carnallite dissolution as dealt with in the preceding sections made the difficulties more serious.

The supervisors of backfilling shifts usually are not familiar with the solubility relationships. However, they know from experience that the more fresh water used before and after a backfilling shift, the smoother the backfilling operations run, and that is all that they are responsible for.

The real problem is the fact that the dangerous consequences of excessive watering of backfill pipelines are not dealt with in German textbooks; on the contrary, available data are frequently distorted in publications for the apparent purpose of exonerating those responsible for serious mistakes.

For these reasons two case histories are presented in some detail in the following.

5.5.2 Case histories, Königshall-Hindenburg potash mine

5.5.2.1 The 1938 flooding

The reader is reminded of the dual role of mine pillars under geological conditions where gas and/or brine reservoirs are present underneath extracted potash beds: the pillars not only have to provide adequate overburden support; even more important is the prevention of dangerous floor deformations as shown in I/5.3.2.

The geological conditions and the development of the reference mine are shown in Figs. I/5-10 to I/5-13. Fig. I/4-12 shows schematically the development of pillar stresses in mining panels. Excessive dissolution of sylvite took place on occasion of both the 1938 and the 1957 floodings. The mine, located in the West German part of the South Harz district, is no longer in operation for potash production.

According to STORCK (1952, p. 4), the 1938 flooding was initiated by excessive extraction in a small sylvinite panel; the resulting floor deformations released brines from isolated reservoirs underneath the mined-out panel. The presence of such reservoirs underneath the potash mines of the district was known; see Table 5-III for brine analyses.

At the time when the 1938 inflow was noticed, the mined-out panel was in the process of being backfilled hydraulically with refinery waste. The exact location of the inflow could not be determined; the conspicuous brines came out of a partially backfilled room. After only a few days, brines which had not been in contact with sylvite appeared at other locations, see Table 5-VI. The sample for the last analysis was taken in a borehole drilled into the floor of the mined-out panel; the pressure reduction in comparison with the first analysis should be borne in mind.

TABLE 5-VI

Analyses of floor brines (g/l), Königshall-Hindenburg mine

Date	Location	$MgCl_2$	KCl	NaCL	$MgSO_4$	$CaSO_4$	Remarks
25.11.1931	Borehole into floor, 799 m level	13.4	14	294.5	-	4.4	Pressure 70-75 bar
25.01.1938	Room N	10	10	294	2	4.5	
11.02.1938	850 m level	7.6	10	297.2	2.5	3.9	Inflow from bed separation void
25.02.1938	893 m level	4.9	10.1	300.7	3.1	3.4	
23.08.1938	Borehole into floor, room D	5.1	16	296	3.2	3.2	30 l/min, pressure 55 bar

The brines collected at a central pumping station and were pumped to the surface. The KCl contents of these brines were 100 g/l during the first week after the beginning of the inflow, 45 g/l after 1 month, 20 g/l after 2 months, and 10 g/l after 3 months.

The latter KCl content may be considered as the original content of the brines; a calculation based on the known amounts of pumped brines indicates that approximately 2000 tonnes of KCl were dissolved in the mined-out panel. The sylvinite pillars are to be considered as the principal source of the KCl in solution. Extensive additional damage to pillars can be assumed. The continuing increase in inflow rates from 300 l/min at the beginning to

2000 l/min after 7 months led to the decision to cease pumping.

An attempt was made to contain the brines within the mined-out area of the mine; for that purpose all access entries between the main shafts and the mined-out area had to be sealed. These attempts failed because of mistakes made in the construction of the entry seals: the fractured stress-relief creep zone around the future seals was not removed to sufficient depths. The rising brines penetrated through bed separation voids in the entry floors; the separation had been caused by buckling due to horizontal creep deformations (STORCK), 1952, p. 5).

10 years later, the two main shafts were sealed against the flooded mine workings as shown in Fig. I/5-10. The operation is described in detail by STORCK (1952). The original composition of the brines had changed considerably as shown by the analyses 1-3 of Table 5-VII. The changes are attributable to

(1) dissolution of sylvite in other mined-out panels,
(2) dissolution of carnallite wherever exposed in mine workings,
(3) mixing with brines released from fracture systems in the roof anhydrite (Main Anhydrite); the brines originated according to Fig. I/2-16.

TABLE 5-VII
Brine analyses (g/l), Könighsall-Hindenburg mine
See text for explanation

Number	Time	Location	$MgCl_2$	$CaCl_2$	KCl	NaCl	$CaSO_4$
1	July 1946	Shaft II, 850 m	41.6	22.9	118.2	189.0	0.7
2	21.06.1948	Sump shaft II	73	15	110	161	1
3	29.04.1949	Pipe through shaft seal	84	10	118	171	5
4	17.01.1949	Main anhydrite, shaft II	231	140	49	18	-
5	04.09.1950	Main anhydrite Int. shaft I	184	178	43	36	-

Analyses 4 and 5 of Table 5-VII are examples of the composition of brines of the latter type. Apparently, extensive solutioning processes in the flooded mine workings caused roof collapses which released brines out of previously isolated fracture systems in the Main Anhydrite.

Surface subsidences were not detected; apparently, the limited extent of the various mined-out panels prevented any significant bending of the main overburden formation (Bunter Sandstone, see Fig. I/5-10). The significance of Fig. I/4-18 is re-emphasized; apparently, individual fracture systems in the Main Anhydrite were not interconnected.

It goes without saying that the hydrostatic head of the brine in the two mine shafts re-established a uniform pressure in the interconnected cavities consisting of mine openings, fracture systems in the roof, and reservoirs in the floor. At the time of the flooding, the gas pressure had been reduced to various degrees, depending on the amount of brines forced out of any individual reservoir. Considerable amounts of brines may have been forced back into the reservoirs until, in May 1939, the brine level in both mine shafts stabilized at the depth of approximately 135 m below surface. It took 16 months to fill the mine workings with brines.

Over the following years, groundwater inflow into the mine shafts above the brine level resulted in different water levels in the two shafts; the groundwater caps forced some brine back into the mine workings. STORCK (1952, p. 5) calculated the brine pressure at the location of the first observed inflow at the depth of 885 m as 93.7 kp/cm^2, less than one-half of the average theoretical lithostatic pressure.

It appears safe to assume higher pressures in the abutment zones of panels in which the rising brines apparently dissolved more sylvite, damaging or destroying the pillars as evidenced by considerably increased KCl contents in samples 1 - 3 of Table 5-VII.

The continuing floor deformations caused by continuing dissolution of potash minerals resulted in the continuing increase of the inflow rates mentioned above.

During the decade following the flooding, creep deformations of the floor rock salt according to Fig. I/4-13A apparently closed most of the fractures through which the floor waters had entered the mine. As a result, the inflow rate during and after the sealing of the main shafts never exceeded 0.9 m^3/min, less than one-half of the final inflow rate in 1938.

STORCK (1952, p. 11) explains this phenomenon as the result of limited groundwater flow from the outcrop area towards the brine reservoirs underneath the mine; such groundwater flow is also assumed for the other case histories dealt with in the preceding text (BAUMERT, 1953, 1955; GIMM and MEYER, 1962). Such hypotheses cannot be accepted because of the gases stored underneath the mines. The reduction in gas pressures, see Table 5-VI, is re-emphasized.

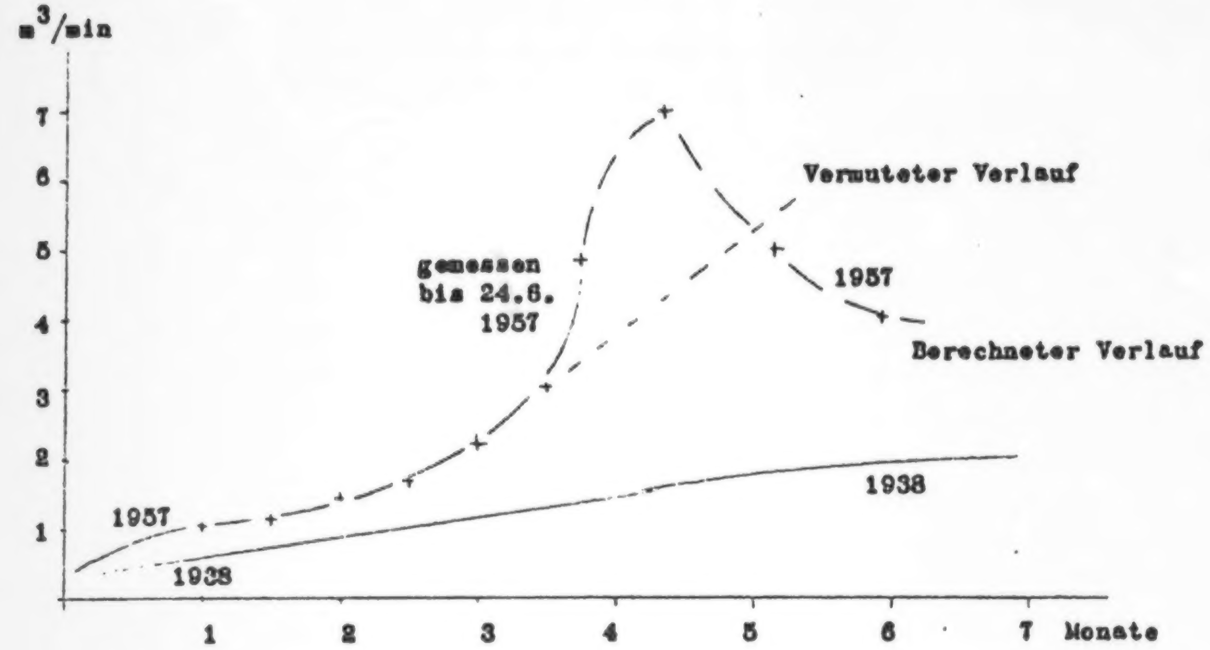
5.5.2.2. The 1957 flooding

Measurements and observations on occasion of the 1957 flooding definitely confirmed that gas pressure was forcing the brines out of individual reservoirs which are not connected to near-surface groundwater. The erroneous assumption of groundwater inflow led to several errors in attempts to control the 1957 inflow. These errors resulted in rapidly increasing inflow rates which finally exceeded 6 m^3/min; the active mine workings had to be abandoned hastily; most of the expensive equipment was left in the flooded mine workings.

Details of the successful sealing of the two intermediate shafts 1 and 2 of Fig. I/5-10 are reported by EBERHARDT (1962). The writer stresses the initial development of the inflow rates: it appeared possible to continue the mining operations until October 1957; at that time, the mining equipment was to be taken to the 665-m level for use in a newly developed area to which access was to be established by the intermediate shafts 3 and 4; thereafter, i.e., in November/December 1957 according to plan, the two intermediate shafts 1 and 2 were to be sealed.

However, in May 1957, an unexpected increase in inflow rates, see Fig. 5-3, forced to change these plans; in June, the pumps could no longer handle the inflow, so the shaft sealing operations had to start immediately. There would not have been sufficient time left for these operations if the increase in inflow rates had continued as in June. However, another unexpected change to the inflow rates provided the necessary time; as can be seen in Fig. 5-3, the inflow rates began to decrease after having reached the indicated maximum. This decrease clearly demonstrates the relationships shown in Figs. I/4-17 through I/4-21.

Apparently, decreasing gas pressures caused the inflow rates to decrease when the floor deformations terminated; the fractures in the floor of the mined-out panel apparently remained at constant widths when nearby mining operations (heavy blasting) ceased. When the brine level in the mine rose above the 820-m level, increasing hydrostatic heads contributed to the further decrease of the inflow rates.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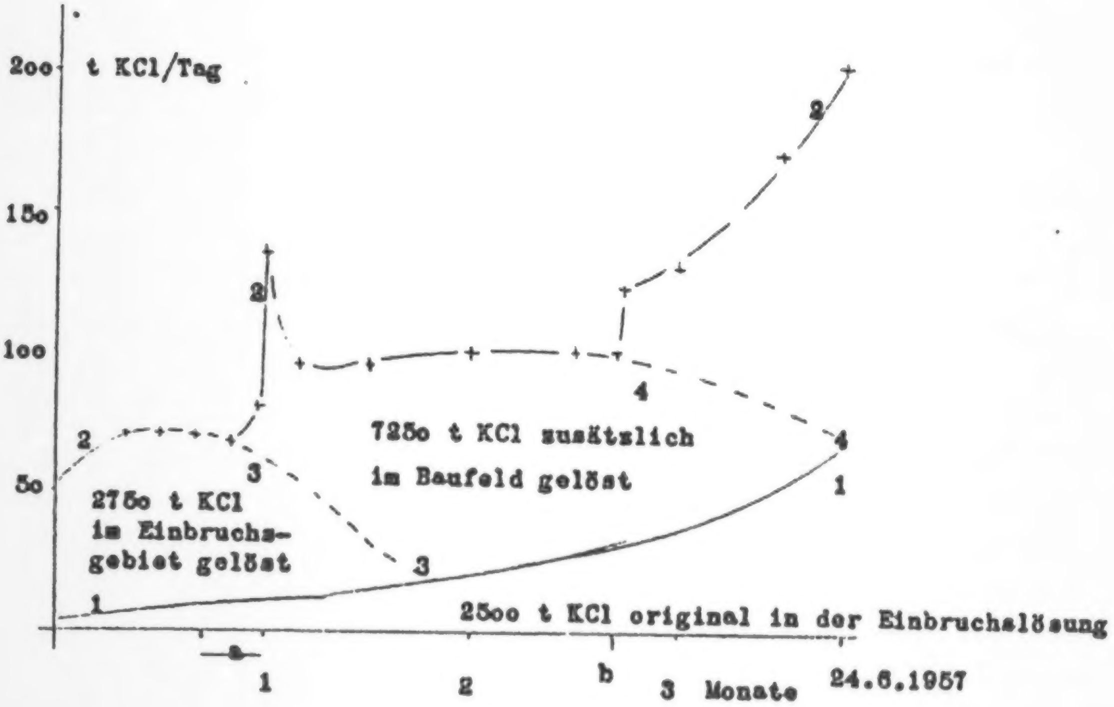
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According to EBERHARDT (l.c., p. 221), the pressure of 96 bars developed at the bottom of the seals in the two intermediate shafts 1 and 2 at the end of September 1957; the first increase above the atmospheric pressure had been observed at the beginning of September 1957. The seals proved tight.

The brine pressure against the bottom of the seals dropped to 9.5 bars in 1961, leaving no doubt of a corresponding reduction of the gas pressure. The gases were released through boreholes drilled to explore a new mining area.

WILKENING (1959, p. 50) reports a drop of the brine pressure from 96 to 61 bars over the first year following September 1957. The subsidences at the 665-m level above the mined-out panel (see Fig. I/5-11) ceased; at some observation points, slight uplifts up to 8 mm were measured. The writer concludes that brine pressures less than 100 bars terminated the creep deformations shown in Fig. I/5-13A.

However, the main overburden formation apparently continued to trasnfer most of its load to abutments around the flooded panel. This is evident from the fact that the drop in brine pressures against the roof to 9.5 bars in 1961 had no significant effect on the subsidences at the 665-m level; measurements to support this statement are not available.

WILKENING (1959) presented his data to support the conclusion (BAAR, 1959b, pp. 51-55) that inadequate support by pillars allowed the floor deformations. HÖFER's (1958b) hypotheses were shown erroneous. The latter writer argued that a confining pressure of 100 kp/cm^2 against the pillars would have halted pillar deformations.

This argument is based on the erroneous assumption that there were pillars left in the mined-out panel. As outlined in detail in I/5.3.2, the first 3 pillars in the center of the panel collapsed in 1956; the brine inflow was reported at the end of February 1957. This writer was assigned to investigate the source of the brines; the collapsed area could be inspected; it had the shape of a dome. There was ample space above the rubble of the collapsed roof shale, as observed at numerous other locations in potash mines of the district (BAAR, 1953c). The open cavity was found dry, with no indication of any brine dripping from the roof. The ventilation system of the mined-out panel was still functioning, preventing any dangerous accumulation of gases.

The pillars in the eastern part of the panel were embedded in backfill. It is assumed that these pillars were damaged, partly due to excessive use of freshwater in the backfilling operations. Considerable temperature increase in and underneath the panel caused excessive floor deformation. More serious damage was caused by formation waters forced up into the mined-out panel; there are reasons to assume that the inflow began during the backfilling operations in 1956.

5.5.2.3 Dissolution of sylvite proved disastrous

With reference to Fig. I/5-11, the following sequence of the mining operations is re-emphasized.

The extraction of 4 rooms (A-D) in 1954 from the 820-m level did not cause any measurable subsidence at the 665-m level; however, considerable lateral pillar deformations were measured (Table I/5-II and Fig. I/5-12).

Subsequently, the rooms underneath the subsidence observation points 15 - 18 were extracted. Backfill operations from the 783-m level commenced while extraction mining continued underneath the observation points 6 - 9. Retaining walls were built in the access openings to rooms A-C at the 820-m level. Room D served as access to the active mining area of the panel.

On April 15, 1956, rooms A - C collapsed; the collapsed area extended into the eastern part of the panel where hydraulic backfill operations were in progress. Undoubtedly, the temperature increase caused by hot refinery waste re-activated the deformations underneath the backfilled area, as indicated by the maximum depths of the measured subsidence trough: prior to the collapse, the maximum subsidence was measured at observation point 15; it shifted slightly towards observation point 12 while the backfilling operations continued.

Room D was not affected by the collapse, apparently because of its limited height of 2-3 m. It continued serving as access to the western part of the panel which was extracted while the eastern part was backfilled.

The backfilling of the eastern part of the panel was terminated approximately ½ year prior to the time reported by EBERHARDT (1962) as the time at which suspicious brines were reported for the first time (around the middle of February 1957). In fact, at that time the outflow of suspicious brines out of the backfilled rooms could no longer be kept secret. The brines were forced through fractures around the retaining walls at the much travelled 820-m level.

For an unknown period of time, unknown quantities of brines had been flowing underneath the floor of the 820-m level towards deeper mine workings, using bed separation voids as pathways. Only after these pathways had become insufficient to release all the formation waters which were forced up into the backfilled rooms, increasing quantities of brines were retained in the backfilled area. The corresponding build-up of a hydraulic head behind the retaining walls then forced the brines through stress relief fractures as reported above.

These facts were established at the beginning of March 1957 when a station for exact measurements of outflow rates was to be excavated in the floor of the access to room A. At this location, an estimated 60 l/min of brines were flowing in bed separation voids out of the panel. The outflow rate underneath the access to room B probably was even higher; it was not determined exactly as there was no time left for such investigations. However, pressure measurements on a pipe through the retaining wall indicated a hydrostatic pressure corresponding to 5 m of brines behind the retaining wall.

On the basis of these findings, the management was urged to have the retaining walls opened immediately to prevent further sylvite dissolution in the backfilled eastern part of the panel; it appeared particularly important to prevent damage to the pillars between the collapsed area and the 820-m level.

Apparently, the inflow of formation waters through the floor of the backfilled part of the panel was a duplication of the 1938 inflow; KCl dissolution from sylvinite pillars was to be expected.

As shown in Table 5-VI, the original KCl content of the formation water was known. The measured quantities of outflowing brines and their KCl contents made it possible to calculate the quantity of sylvite leached out of pillars while brines were held back in the panel. These quantities are plotted in Fig. 5-4 as tonnes KCl per day. The quantities of dissolved KCl were expected to decrease quickly when the brines were allowed to flow freely out of the panel. For this reason the retaining walls in the accesses to rooms A - C at the 820-m level had to be opened immediately. This conclusion proved correct: on March 7, 1957, the retained brines had been released; the KCl content of the brines flowing out of room B decreased to 100 g/l. It decreased further to 90 g/l on March 15, and to 73 g/l on March 22.

Room B was representing the deepest part of the synclinal structure of the panel; it collected most of the outflowing brines. On March 14, when room B was inspected, the total outflow measured 550 l/min; 450 l/min were seeping out of the rubble of the collapsed area, flowing at the surface of the underlying rock salt where no harm could be done. Room B between the 820-m level and the collapsed area was open over the length of 40 m. The pillars were found in relatively good condition. The rubble in the collapse area had retained the backfill, which had been piped in from the 783-m level. The brines were flowing out of the room without contacting the sylvinite pillars. Accordingly, the further decrease of dissolved quantities of KCI shown in Fig. 5-3, curve 3, could be expected.

The remaining 100 l/min of the total measured outflow came from room A; the quantities of dissolved KCl were also decreasing, but at a slower rate. On March 14, this outflow still contained approximately 130 g/l KCl, as shown by EBERHARDT (1962, fig. 2). It must be stressed that the data presented by the writer do not indicate the KCl contents of the total outflow but rather those of the 100 l/min flowing out of room A. The writer's error is apparent from the analysis presented for the total outflow (l.c., Table 1): on March 2, the total outflow contained 125 g/l KCl, decreasing to 29 g/l on August 14 when the last brine sample was taken.

Two weeks after the outflow of suspicious brines had been reported, i.e., one week after the retaining walls in the accesses of rooms A-C had been opened, the development of the quantities of dissolved KCl was definitely encouraging. At that time, no brines were flowing out of room C; this clearly indicated the eastern part of the backfilled panel as the area where gas pressure was forcing the brines up into the mine workings. This writer suggested to intercept the rising brines by boreholes to be drilled into the floor rocksalt underneath the inflow area, and to reduce the inflow by grouting. At the same time, attempts to locate the gas reservoirs should be made so that the gas pressures could be reduced by releasing the gases through boreholes to the effect that eventually no more brines would be forced up into the mine.

That proposal was dismissed for the following reason: according to STORCK (1952), the inflowing brines had connections to groundwater aquifers near the outcrops of the Zechstein strata at considerable distances; the same opinion was promoted by BAUMERT (1927, 1953, 1955) and other writers as previously outlined in detail. The facts summarized in Table 5-VI, particularly the considerable reduction of brine pressures underneath the 1938 inflow area in a borehole, were ignored.

Instead, apparent belief in the possibility of increasing the stability of sylvinite pillars by hydraulic backfilling resulted in a decision which gave the fatal blow to the mine: from March 22 to 30, 1957, the open part of room B was backfilled up to the top of the rubble in the collapsed area. For that purpose, a pipeline was laid through the retaining wall at the 820-m level, and the retaining wall was closed. In this way, the outflow of brines out of room B was virtually terminated.

The predictable result is shown in Fig. 5-4: the brines, which left the inflow area through room B without doing any more damage by KCl dissolution, were forced to find new pathways through the backfilled area. Disregarding the initial peak value of the KCl contents which reflects the KCl contents of the backfill brines, one can see the daily quantities of dissolved KCl increasing to twice the quantities carried out of the panel prior to the backfilling of room B. Apparently, the dissolution of sylvite from pillars which were still providing at least some restraint against further floor deformations resulted in the increase in outflow rates.

Apparently, the continuing increase in outflow rates prompted a last-ditch effort to control the inflow by grouting from the 665-m level; a borehole drilled into the roof anhydrite above the collapsed area was connected by a pipeline to a mobile grouting unit of the type used in oil-field operations; the unit, positioned at the surface, could have provided considerable grouting pressures if required. However, within a few hours in each of several attempts, the cement slurry appeared with the outflowing brines at the 820-m level.

The grouting attempts, starting on May 15, apparently were based on the hypothesis that groundwater flowing through fracture systems of the roof anhydrite was the source of the brines. Needless to say that such attempts were useless as the brines originated from reservoirs below the extraction level. However, the last attempt on June 14 resulted in another considerable increase in KCl contents of the brines which left the backfilled panel; as shown in Fig. 5-4, the quantities of dissolved KCl increased to 200 tonnes per day.

Apparently, the repeated grouting operations blocked pathways used by the outflowing brines, but not those used by the inflowing brines which kept rising under gas pressure from reservoirs underneath the panel. The brines in the backfilled eastern part of the panel rose to the 783-m level, dissolving sylvite from pillars which had not been contacted previously; as a result, the floor deformations were re-activated, allowing the inflow rates to jump from 3 m^3/min to more than 6 m^3/min as shown in Fig. 5-3.

It was only the unexpected, but predictable decrease in inflow rates due to decreasing gas pressures shown in Fig. 5-3 which provided sufficient time to complete the sealing of the two access shafts to the flooded mine workings. Attempts to make a story of alleged careful planning (EBERHARDT, 1962) out of a series of grave errors are deplorable. Even more deplorable appears the attitude of the editor of the respective periodical who refused to publish necessary corrections.

5.5.3 Case history Bischofferode potash mine

The Bischofferode potash mine operates north, west, and east of the flooded mine dealt with in 5.3. Mine development to the north is limited by the proximity of solutioned areas along the northern edge of the South Harz sub-basin.

Gases encountered in the northernmost mine workings proved beyond doubt that salt solutioning by groundwater had no effects on the extracted potash bed, and on the impermeability of the protecting salt sequences above and underneath the mine workings. In 1914, huge amounts of gases were released as reported in detail in I/4.6.3.

STOLLE (1958) and GIMM and MEYER (1962, pp. 404-407) provide detailed reports on the circumstances which caused the development of the inflow rates of curve 2 of Fig. I/4-21. The interested reader is referred to these publications. The inflow started in 1954; the respective area in the NW-corner of the mine was extracted 1937-1948, and backfilled 1940-1949. The apparent cause of the inflow was the dissolution of a carnallite lense up to 1 m thick in approximately 10 pillars of the mined-out area (BAAR, 1944, map and section).

Table 5-VIII shows the composition of brines which began flowing out of the backfilled panel in 1954. The samples for series 2 were taken next to the carnallite lense in the pillars of the backfilled panel. The analysis shows $MgCl_2$ contents higher than those of "normal" backfill brines, see Tables 5-I and 5-II. The $MgCl_2$ contents and the lack of H_2S indicate that these brines had leached carnallite from the respective pillars. The out-

TABLE 5-VIII

Brine analyses (g/l), Bischofferode potash mine;
See text for explanation.

Series 1

Year	$MgCl_2$	$MgSO_4$	KCl	NaCl	$CaSO_4$	H_2O	H_2S
1954	69	16	101	202	n.a.	854	n.a.
1955	1.48	3.66	7.53	310.28	3.59	879.44	0.0025
1956	1.42	3.82	6.03	307.94	3.40	882.37	0.017
1957	1.18	3.94	6.57	303.15	3.35	887.80	0.011
1958	1.34	3.91	8.88	308.10	3.64	884.12	0.014
1959	1.45	3.86	11.89	305.10	3.44	881.25	0.004
1960	2	4	10	307	3	884	0.022
1961	2	4	13	303	3	886	0.007

Series 2

1955	112.4	12.6	45.2	151.0	-	873.90	-
1956	115.24	12.66	83.08	146.52	-	881.50	-
1957	108.72	11.85	81.14	146.71	-	886.58	-
1958	outflow terminated						

flow at the rate of 3 l/min terminated in 1958.

The bulk of the brines were flowing through the backfilled area to the more distant locations 1 and 3. The 1954 analysis at location 1 shows the typical composition of brines used in backfilling operations. Changes in KCl contents over the following years indicate sylvite dissolution in the backfilled area. Investigations by core drilling (STOLLE, 1958) left no doubt of the origin of the brines: they were stored in reservoirs underneath the rocksalt, and were forced up into the mine by gas pressure.

The latter writer (l.c., p. 23) reports the inflow rates plotted in Fig. I/4-21. The latest available inflow rate is listed as 40 l/min in 1965 (GIMM 1968, p. 479); the writer's listing of 100 l/min as maximum previous inflow rate is apparently incorrect.

GIMM and MEYER (1962) and GIMM (1968) are trying to establish a relationship between the length of the time period between extraction and backfilling and the causes of dangerous deformations of the floor salt sequence which release brines and/or gases. Their hypothesis resembles that of HÖFER (1958) who also postulates that mined-out rooms must be backfilled as soon as possible in order to prevent damage to the pillars by excessive creep deformations.

In cases where pillars are damaged or completely dissolved on the occasion of backfilling, dangerous floor deformations apparently occur sooner when mined-out panels are backfilled. On the other hand, it appears advantageous to delay the hydraulic backfilling of isolated carnallite areas until floor deformations in surrounding mined-out areas have released sufficient volumes of gases so that the gas pressure is reduced sufficiently.

Needless to say that a sure way of reducing gas pressures in isolated reservoirs is to bleed the gases off through drill holes prior to extraction mining, see 3.5; an example of successful application of exploration drilling to remove gases (EHRHARDT, 1980) is dealt with in 1.2.2.

CHAPTER 6

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CHAPTER 6

UNCONTROLLED SOLUTION MINING

6.1 CONCEPTS OF GALLERY OPERATION QUESTIONED

The spacing of wells in brinefields to be operated in so-called galleries may be determined "possibly with more love for symmetry or regularity than with reason" (BAYS, 1963a). Hydrofracing to connect wells frequently results in unexpected connections, and the planned size and shape of support pillars for overburden control is not achieved - if at all such considerations enter the planning of brinefields.

If and when surface displacements cause damage to buildings, the interpretation of the mechanism of overburden displacements is frequently based on assumptions which may be questionable. The main reason why assumptions have to be made is the lack of information on the actual size and shape of the cavities created by brining.

Lack of reliable measurement data on surface subsidences and lateral displacements often makes reliable assessments even more difficult.

The planning of brinefields is frequently described in great detail; however, follow-up publications on surface displacements fail to appear. One example may be cited: MAIR (1963) describes the planning of a regular brinefield near Windsor, Ontario, Canada; "it was originally planned to connect 18 wells in 6 groups of 3 and to attempt to keep these groups separate". However, "undesired connections were made and washed out not only between groups of wells in the same row but between rows as well". 4 groups of 2, 3, 6, and 7 interconnected wells resulted from undesired connections.

The detailed surface displacement data presented in the following case histories must not be generalized. Mechanisms of short-term and/or long-term surface displacements depend strongly on local operational and geological conditions; considerable differences are to be expected in cases where different conditions govern the overburden reactions to salt removal.

The reader is specifically cautioned against generalizations of measurements and observations made above brinefields at shallow depths.

It must be borne in mind that local geological conditions may differ to such an extent that comparisons between brinefields are totally inadequate.

Caution is especially required regarding postulated mechanism of sinkhole formation due to salt solutioning. The subject matter, dealt with in a number of recent publications, needs clarification.

Recent progress in solution mining techniques to form single cavities of predetermined shape is to be acknowledged. However, there are apparent disagreements as to the most favorable shape of cavities, see I/4.2.4.4.

The interested reader is urged to study carefully the discussion of problems associated with uncontrolled solution mining presented by BAYS (1962a). As the writer puts it: "The better understanding of rock mechanics and subsurface movements will greatly benefit the knowledge about the processes underground for salt solution extraction".

BAYS (1963a, p. 467) describes "significant uncertainties in current salt solution extraction operations" as follows: "The change from single-cavity or naturally cross-connected wells...to fracture-connected has brought about many changes, some without precedent or parallel in older operations...Lack of experience with these new methods makes difficult such matters as...the optimum spacing of wells...there are numerous opportunities for improvements as data are accumulated and more precise information is measured by the operators".

The writer refers to "experience derived almost entirely from bedded salts...in Michigan, New York, Ohio, West Virginia, Ontario, and possibly other areas".

Referring to "the random uncontrolled solution responsible for much of the well known surface subsidence damage of England, France, and elsewhere in the past," the writer makes the following important statement regarding subsidence and surface displacements caused by solution mining of rocksalt: "The inevitability of compensating movements, subsurface adjustments, and in most instances surface movements as a product of the creation of cavities (in salt deposits) is gradually becoming recognized".

"The frac-connected gallery operations thus offer the promise of less hazardous movements and possibilities of surface subsidence than did preceding methods of salt solution extraction. However, no assumption is justified that these newer operations have repealed the more newly-discovered laws of rock mechanics or have obviated the necessity to recognize that compensating movements, possibly surface subsidence, are inevitable to result from extraction. The degree of change from older operation remains uncertain."

The writer (l.c., p. 478) stresses an extremely important aspect of well abandonment: "In a solution cavity, the roof will settle until hydraulic buoyancy or the compressive load is taken by the fluid in the cavity and the roof is supported. If the cavity fluids can escape through old well bores to overlying zones or to surface drainage such support will never result".

This statement must not be misunderstood; the writer refers to full support of the overburden by fluids which are sealed in individual salt cavities. Eventually, the fluid pressure becomes the equilibrium pressure necessary to prevent any further deformation. The reader is referred to Figs. I/3-7 and I/3-13 which show the utilization of such equilibrium pressures for the determination of stresses around dry mine openings in salt rocks.

According to BAYS (1963b, p. 577), "the creation of a void in the subsurface, the walls of which are water-wet salts of a highly plastic nature, puts into effect compensating movements in the rock. These are counteracted by the fluid pressure of the cavity, and as long as roof spans are such that elastic limits are not exceeded the movements proceed in a predictable fashion until equilibrium of geostatic pressures and fluid pressures in the cavity are reached."

"Usually this is within five years after creation of the relatively small volume typical storage cavity, and thereafter as pressures fluctuate there is a slow responding fluctuation within the rocks."

The latter statement, of course, must not be applied to impermeable salt rocks as shown in detail in Volume I of this text.

It is re-emphasized that partial overburden support, amounting to roughly one half of the overburden load, is provided by the brines in any salt cavity even if brines can escape. Eventually no cavity may be left due to continuing deformation, see 4.2.

Brines squeezed out of salt cavities result in flowing wells or in groundwater contamination.

Reliable information on flowing abandoned brine wells is not available, probably due to the fact that many older brine wells are not properly cased. Brines forced out of shrinking salt cavities may enter groundwater aquifers, and may be diluted to an extent that makes their detection difficult, if not impossible.

BAYS (1963a, p. 478) is definitely right in stating that "the general knowledge of rock mechanics could be greatly enhanced by pressure data on abandoned cavities through observation wells equipped for that purpose". As a matter of fact, such data are available, see 5.5.2.

Needless to say that useful data can also be obtained on salt cavities which are utilized as storage caverns. It is difficult to find reasons why this opportunity of improving the general knowledge of rock mechanics of salt cavities is widely ignored. Most writers promote hypotheses developed in the laboratory on cavity models, although most laboratory experiments cannot simulate adequately the variable in-situ conditions encountered in salt deposits.

BAYS (1963a) stated that gallery production "became almost the universal practice in salt extraction over a very short span of time".

However, uncontrolled overburden displacements became much more serious than "the widely publicized surface subsidence of February 19, 1954, just south of Windsor, Ontario"; this event, featured as sinkhole formation in other publications, is dealt with in 6.3.

BAYS (l.c., p. 472) fails to mention the apparent need for wider spacing of wells which extract salt from great depths.

The writer (l.c., p. 479) regrets "the paucity of accurate data regarding older operations", stressing that "significant data as to repair work, experiences of operating, logging, and the like can only be secured at the appropriate times".

"Another element of data for the future that plainly merits attention is the setting of surface benchmarks and the regular survey thereof. Unless control surveys are started contemporaneously with the start of extraction and firmly geared to reliable distant reference points, no real appraisal of the surface effects or the direction of solution extraction is possible. Unless such surface data are obtained by the industry the ultimate safety of the surface of their own and their neighbor's property cannot be assured".

Regarding the necessary support of the overburden to prevent surface damage, the writer (l.c., p. 479) points out: "If adequate data are obtained it is obvious that there are likely to be sufficient data to aid the understanding and permit the necessary protective measures by operators of the newer solution extraction fields to provide adequate support or surface protection. However, present fields in most cases represent extensions or replacements of older operations. Many of these are suspect, even though abandoned, that some day -- 25 - 30 or more years hence -- they may show surface subsidence, draw effects, or even possibly catastrophic sinkhole-type surface failures".

"While advance calculations of subsidence and adequate control may prove feasible with the newer operations, the associated older operations must remain unknown quantities for long periods -- but represent problems that present and future operators should be prepared to live with".

This writer has nothing to add to the quoted assessment of older brining operations. The case histories presented in Chapters 3 and 4 provide additional evidence.

As shown in Chapter 7, the collection of reliable subsidence data aided the understanding of surface displacements above conventional salt and potash mines. In contrast, uncontrolled solution mining continues to cause surface damage which resembles the damage reported in 3.2, 4.4, and 4.5.

The following case history deserves particular attention because of the comprehensive data collection.

6.2 SURFACE DISPLACEMENTS AT TUZLA, YUGOSLAVIA

6.2.1 Historical and geological data

The Tuzla basin, located approximately 150 km west of Belgrade, contains Yugoslavia's only known commercial salt deposit. The salt basin is very small, covering an area of approximately 1.5 km^2.

The salt is extracted by uncontrolled solution mining which caused, and continues to cause, destructive damage to buildings in the town of Tuzla.

Publications dealing with rock-mechanical aspects of the surface displacements indicate that most writers are misled by their reference publications; this statement applies to the papers discussed by BAAR (1979), and particularly to the publication by JEREMIC (1975). The latter publication requires the corrections presented in 6.2.4.

The following outline of the history and the geology of the Tuzla salt deposit is based on data published by OSMANAGIĆ and JAŠAREVIĆ (1977) and re-published by STEVIĆ et al. (1979).

According to the writers, the industrial production of brines through wells began in 1886. Fig. 6-1 shows the production well zone, the boundary of the salt deposit, and the boundary of a protective pillar. The pillar is approximately 200 m wide and separates the brinefield from an area to be extracted by conventional room-and-pillar mining.

As more than 230 wells were drilled in the Tuzla basin, the salt boundaries shown in Fig. 5-1 are well defined. The depths to the top salt bed increase slightly towards the NW. There are four distinct salt beds with the total thickness of approximately 200 m. The writers emphasize the considerable marl content (30 - 50%) of the bedded salt series. The overburden also consists of banded marl with some sandstone interbeds.

The uppermost salt bed at depths from 100 - 300 m is almost totally extracted; its thickness was approximately 15 m. Presently, apparently since 1956, the next underlying salt series is being mined; its thickness is approximately 60 m.

Fig. 6-3 shows cross-sections along the line J-J of Fig. 6-2. Details of petrography and stratigraphy are not provided.

The writers (l.c., p. 521) emphasize: the banded roof marls of the solution-mined salt beds and the solution residues represent one single aquifer which is recharged through the outcrops of the evaporite strata, see Fig. 6-4. The recharge by infiltration of rainwater takes place at the rate of 8.45 l/sec; the Jala river (on the southern side

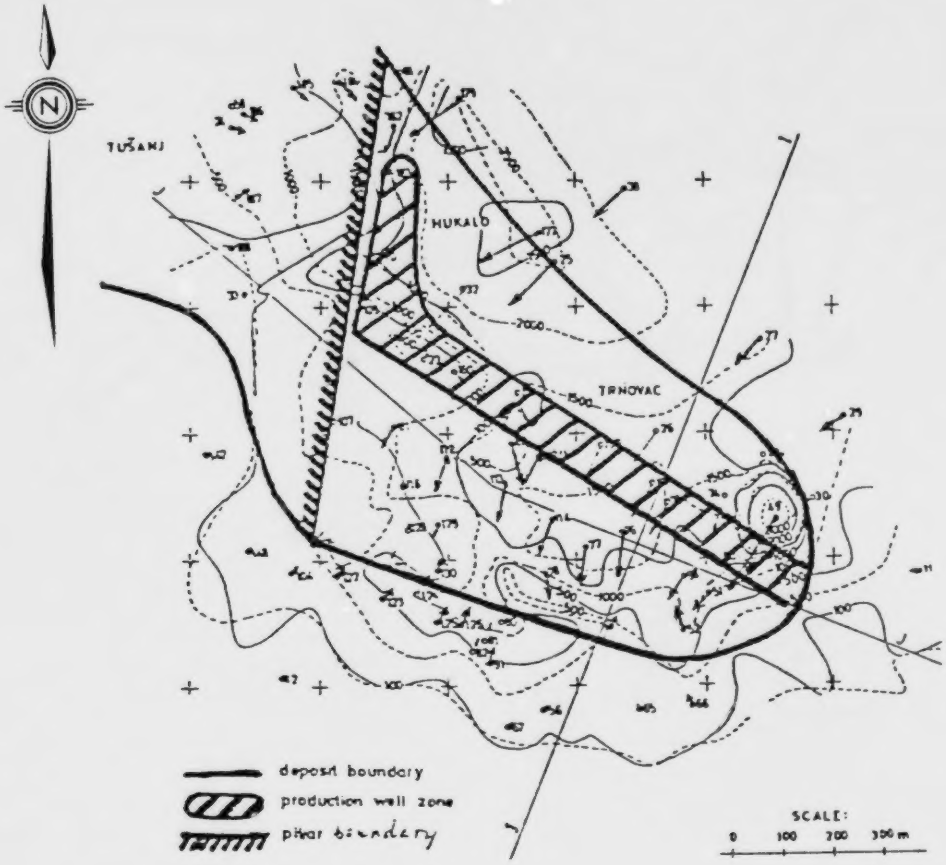


Figure 6-1: Solution mining at Tuzla salt basin, Yugoslavia (modified after OSMANAGIĆ and JAŠAREVIĆ, 1977, Fig. 3).

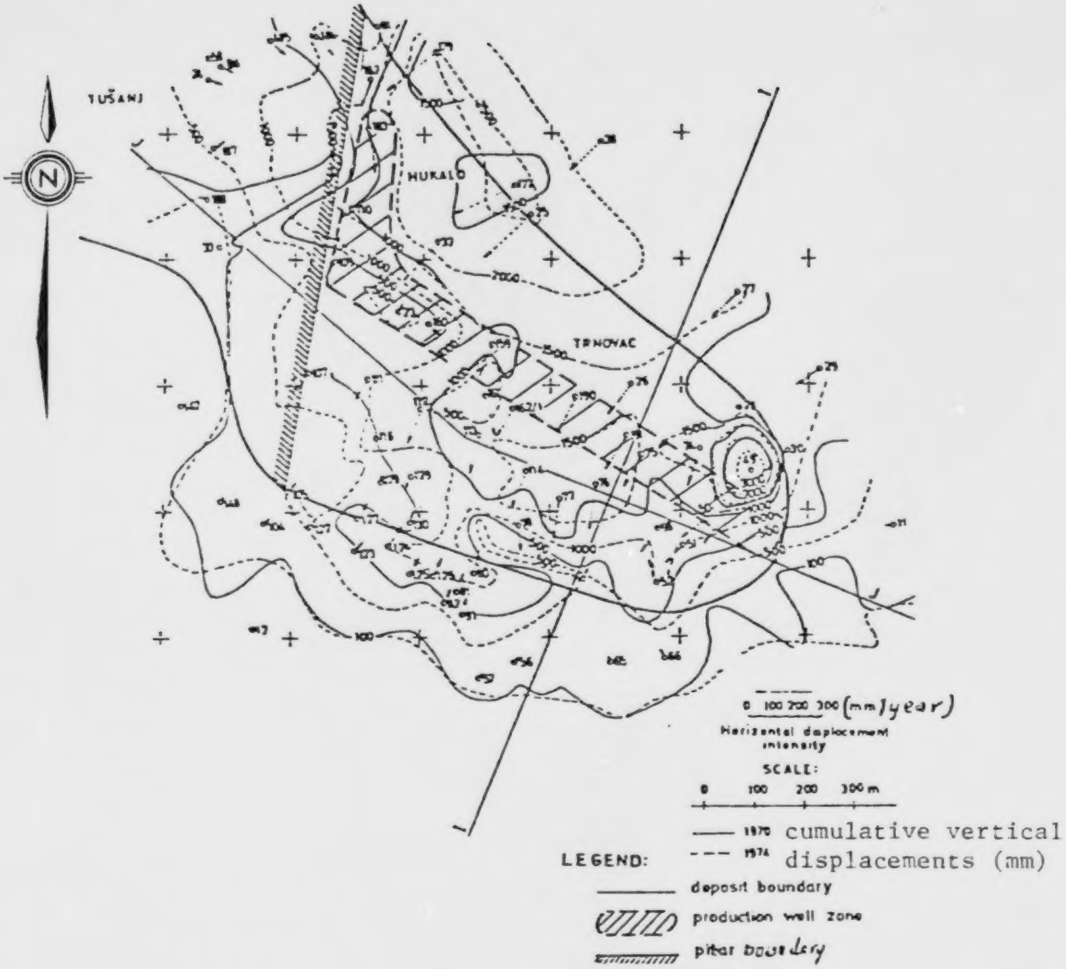


Figure 6-2: Surface displacements at Tuzla salt basin, Yugoslavia (from OSMANAGIĆ and JAŠAREVIĆ, 1977, Fig. 3).

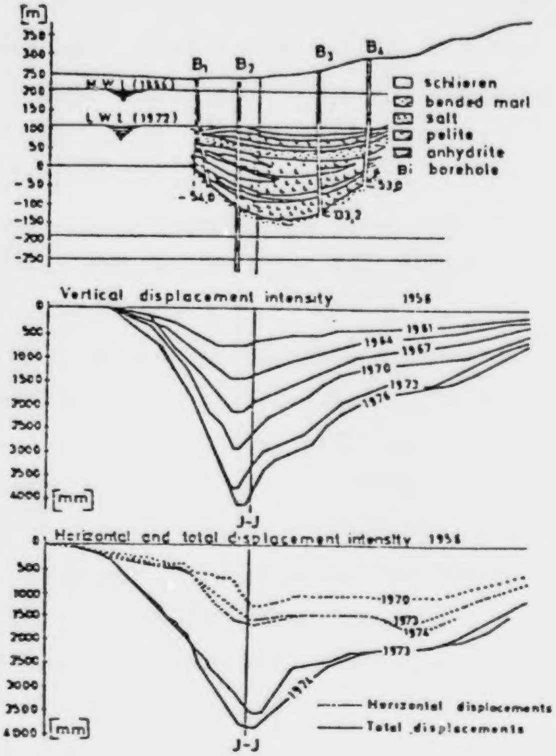


Figure 6-3: Stratigraphy and displacements 1956-1976 along line J-J of Fig. 6-2 (after OSMANAGIĆ and JAŠAREVIĆ, 1977, Fig. 1).

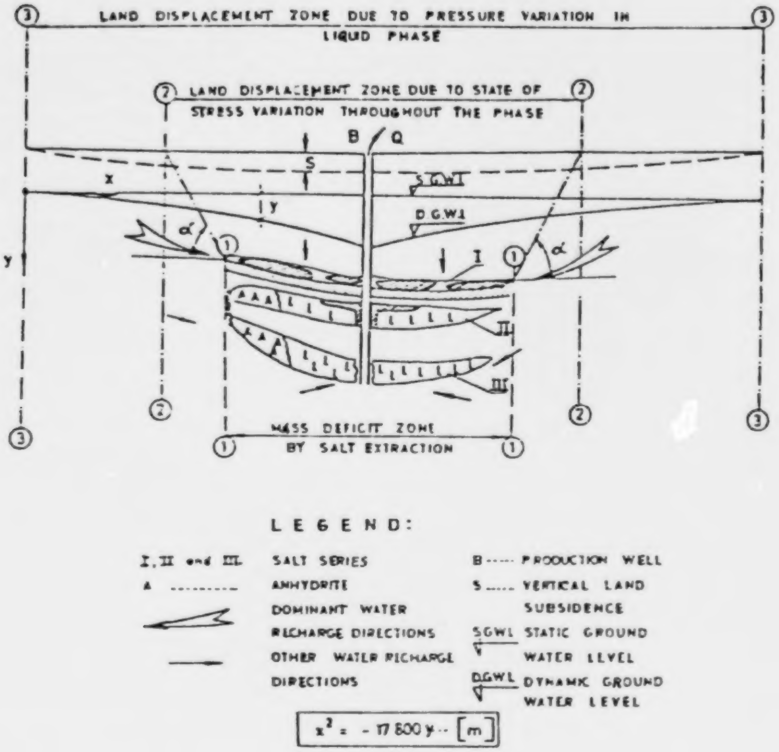

③ LAND DISPLACEMENT ZONE DUE TO PRESSURE VARIATION IN LIQUID PHASE ③
② LAND DISPLACEMENT ZONE DUE TO STATE OF STRESS VARIATION THROUGHOUT THE PHASE ②
B
Q
S
SGWL
x
y
DGWL
α
①
I
II
III
MASS DEFICIT ZONE BY SALT EXTRACTION
LEGEND:
I, II and III SALT SERIES
A ANHYDRITE
DOMINANT WATER RECHARGE DIRECTIONS
OTHER WATER RECHARGE DIRECTIONS
B PRODUCTION WELL
S VERTICAL LAND SUBSIDENCE
SGWL STATIC GROUND WATER LEVEL
DGWL DYNAMIC GROUND WATER LEVEL
x² = - 17 800 y .. [m]

Figure 6-4: Assumed ground water flow directions and assumed shape of draw down cone at Tuzla salt basin (from OSMANAGIĆ and JAŠAREVIĆ, 1977, Fig. 7).

of the salt deposit) and the Solina river (on the eastern side) contribute 28.55 l/sec on average.

Reference is made to a zone of porous limestone through which the river water enters the aquifer, see the large arrows on Fig. 6.4. Karst features are not mentioned. However, intensive karstification of the non-salt evaporites near the outcrops can be assumed, as it is observed elsewhere under comparable conditions, see Chapter 4.

Brine pumping in excess of the available recharge water made the groundwater level drop by 107 m from 1886 to 1972, see Fig. 6.3. Details of this "drawdown" are discussed in 6.2.5.

The uncontrolled solution mining caused considerable surface displacements associated with destructive damage to buildings. The maximum vertical subsidence over the "last sixty years" prior to 1973 is given as 7.75 m (l.c., p. 523). Fig. 6-5, credited to JAŠAREVIĆ (1975), is supposed to show the relationship between the salt production and the development of the following features: A maximum surface subsidence, B area of subsidence, C volume of the subsidence trough.

The surface subsidence is called time-dependent. This is not acceptable for the following reasons: the curves of Fig. 6-5 are cumulative curves, and there is no question as to the increase of the continuing salt production with time. However, the increase in salt production is not depending on time, but on limitations set by the recharge conditions in the Tuzla basin.

In fact, Fig. 6-5 relates the maximum subsidence A to cumulative amounts of produced salt rather than to time.

As the subsidence data are plotted against the known figures for salt produced, the production scale can be converted into a time scale.

The maximum subsidence curve A clearly shows deceleration since approximately 1960, while curve C (calculated volume of subsidence) is shown as increasing more and more with time, particularly during a few years before 1973.

The subject matter is also dealt with by JEREMIC (1975) and requires further discussion, see 6.2.3.

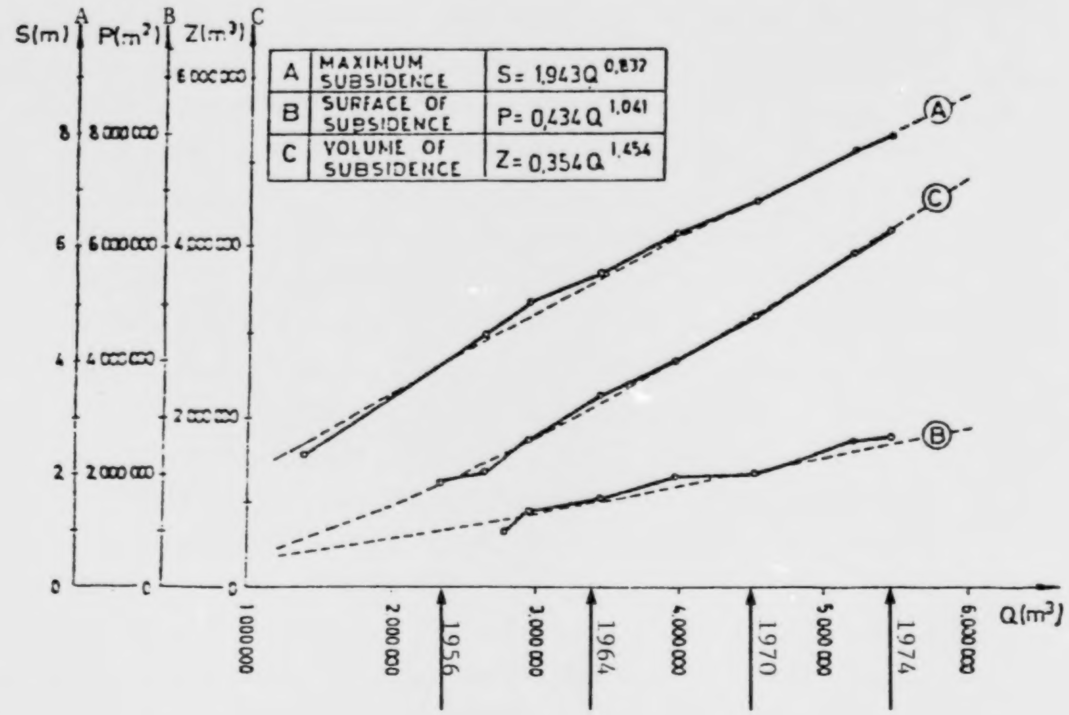


Figure 6-5: Cummulative subsidence data vs. salt production, Tuzla salt basin (after JAŠAREVIĆ, 1975).

6.2.2 Geodetic measurements

OSMANAGIĆ and JAŠAREVIĆ (1977) give the following account of the triangulation and levelling network above the Tuzla deposit.

The triangulation traverses include 230 stations. The distances between the stations are measured with a mean error of 4 - 5 mm.

Precise levels are determined on 550 stations with an accuracy of 3 mm or better.

The stations consist of re-inforced concrete in the form of a truncated cone. The depth at which these monuments are anchored is not indicated. This writer considers the lack of exact anchor depths as a serious shortcoming of the reference paper as discussed in more detail in 6.2.4.

Systematic measurements were taken once each summer since 1956. The data are used to prepare annual and summary maps, and sections of the area affected by the uncontrolled salt extraction. Some results of this work are presented and discussed.

The writers present the data on vertical and horizontal surface displacements on Fig. 6-2. The contour lines of vertical displacements on this figure should be ignored because of apparent errors, particularly because of the lacking closure of some contour lines at the northern side of the deposit. OSMANAGIĆ (BAAR, 1978, written communication) was made aware of these errors and apparently pressed for corrections which are shown on Fig. 6-6 (STEVIĆ et al., 1979).

However, the contour lines on Fig. 6-6 and the extension of JAŠAREVIĆ's (1975) evaluation of Fig. 6-5, see Fig. 6-7, are even more questionable. The following detailed discussions appear necessary.

6.2.3. Vertical surface displacements

OSMANAGIĆ and JAŠAREVIĆ (1977, p. 523) place special emphasis on the maximum vertical displacement of 4281 mm near benchmark 32. The writers estimated that 325 mm of the vertical displacement occurred during the last year prior to the measurements in 1973. The reason why the writers resort to an estimate becomes apparent from Fig. 6-5 (JASAREVIĆ, 1975): the writer intends to prove accelerating subsi-

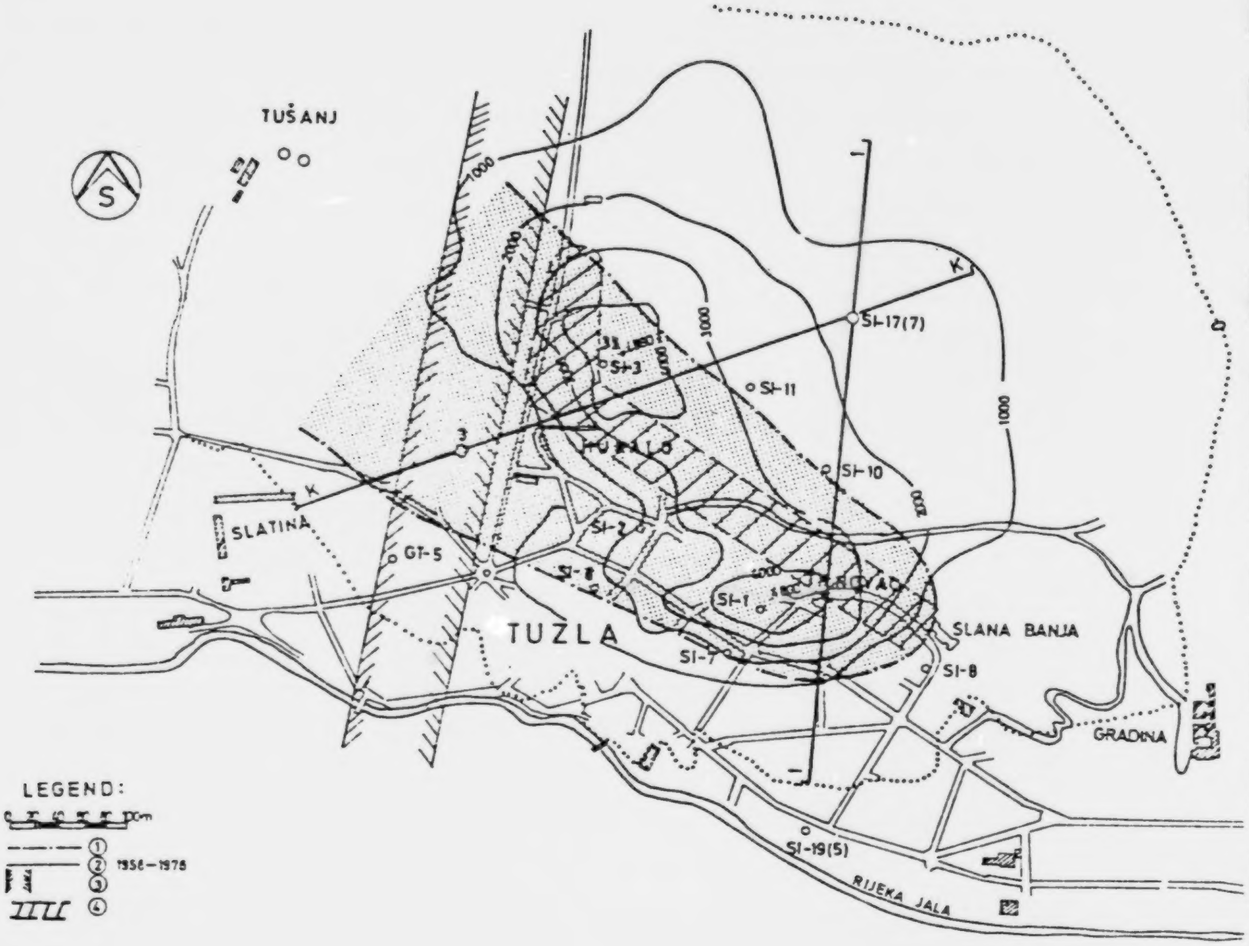


Figure 6-6: Revised subsidence map, Tuzla salt basin cf. Fig. 6.2 (after STEVIC et al., 1979, Fig. 1)

(1) deposit boundary,

(2) subsidence isolines (mm),

(3) pillar,

(4) production well zone.

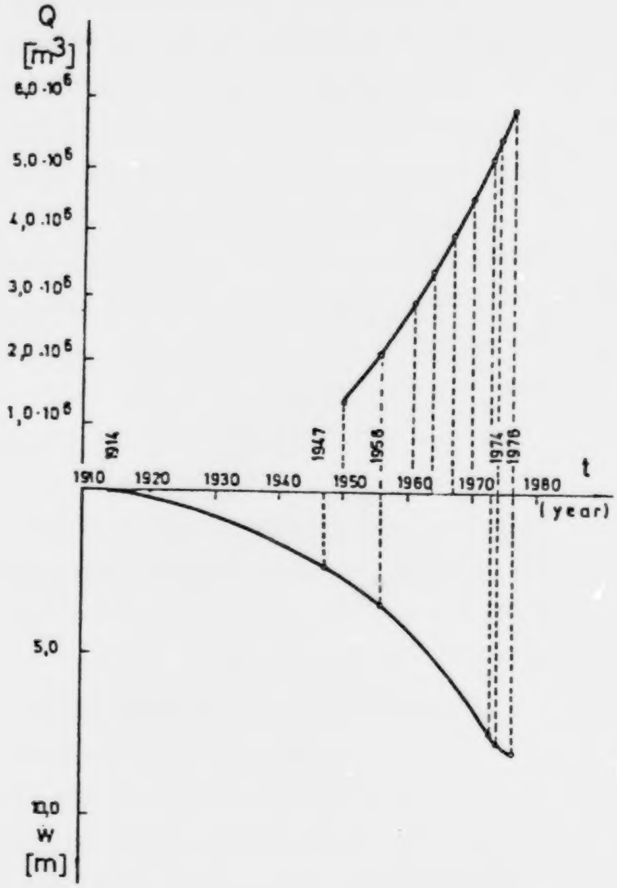


Figure 6-7: Salt production (Q) and maximum subsidence (w) versus time (t) (after STEVIC et al., 1979, Fig. 2).

dence as discussed at the end of 6.2.1.

Fig. 6-5 shows the volume of the surface subsidence trough (curve C) increasing at an accelerating rate in contrast to the apparent deceleration of the maximum subsidence (curve A).

In fact, however, curve A shows a virtually constant slope, i.e., a constant subsidence rate since approximately 1960.

Differences in the development of localized subsidence cannot be interpreted without complete knowledge of the production records of all brine wells in the respective brinefield, see Chapter 4.

In all probability, some of the production wells in the Tuzla basin were shut down temporarily or completely because of casing problems. Some wells may have been replaced as reported from other brinefields where much less surface displacement occurred, see 4.4 and the following text.

Fig. 6-3 shows the maximum vertical displacement from 1956 to 1976 (230 mm/yr on average) neither near benchmark 32 nor near benchmark 49, both located north of the production well zone, see Fig. 6-2. The maximum vertical displacement at the estimated rate of 325 mm/yr is shown on section J-J near its intersection with section I-I, i.e., south of the production well zone.

At this point, it is emphasized that the section $B_1 - B_4$ (i.e., the top section) of Fig. 6-3 refers to the section line I-I rather than to the section line J-J; according to OSMANAGIĆ (1978), the section B_1-B_4 is a schematic geological profile, showing elevations + MSL. Needless to say that the Jala river, see Fig. 6-6, runs along the deepest elevation, i.e., near B_1 at the approximate elevation + 250 MSL.

The surface subsidence troughs of Figs. 6-1 and 6-2 exhibit the characteristics of subsidence troughs caused by conventional mining, see Fig. 7-1. The lack of symmetry with regard to the production well zone indicates preferred recharge from the Jala river. Karst features appear to run approximately in E-W directions.

The evaluation of the measurement data is shown in two versions, Fig. 6-5 and Fig. 6-7: (1) the original version credited to JAŠAREVIĆ (1975), (2) another version extended to 1976 (STEVIĆ et al., 1979). The latter version is significantly changed: 1. the production scale of Fig. 6-5 is replaced by a time scale; 2. the extension of the subsidence curve beyond 1973 clearly shows considerable deceleration in sharp contrast to the original version and to the theoretical postulates behind it. A detailed discussion follows in 6.2.5.

JEREMIC (1975, Fig. 4) shows a surface subsidence map which differs greatly from Figs. 6-1 and 6-2. The writer fails to provide a scale; however, the general shape of his zero contour line resembles the boundary of the salt deposit, see Fig. 6-2. Apparently, the writer uses data obtained from 1956 to 1965. His map shows "four concentric zonal areas" around the so-called Tuzla sinkhole in the centre of what is called "collapsing deformation" (l.c., p. 215).

In the writer's unusual terminology, "collapsing deformation" means vertical displacement which causes the collapse of buildings: "deformation results just by the surface structures sliding down and the sink hole is filled with fragmented rock and water" (l.c., p. 216). "The zone of collapsing deformations is delineated by a contour of vertical displacement of 70 cm to 170 cm". The writer believes "that horizontal deformations were of insignificant magnitude" inside his 70-cm contour line.

The so-called sinkhole is shown on a photograph (l.c., p. 216); it appears to be an ordinary pond which already existed when the surrounding buildings were erected. The buildings show no damage.

The writer fails to indicate when the photograph was taken; apparently, it is a rather old photograph. It is inconceivable that a water-filled pond persists in the centre of an area under which the groundwater level dropped considerably because of the lack of recharge water.

The writer believes in "shear rupture" of buildings between the contour lines of 20 and 70 cm of vertical displacement, and in "extension rupture" between the zero and 20-cm contour lines. Only horizontal movement is postulated outside the zero contour line of vertical displacement.

This writer, following a written request from the Organizing Committee of the respective Rock Mechanics Symposium, submitted a critical discussion of JEREMIC's pre-published paper for publication in the proceedings.

However, the criticized paper was included in the proceedings, while this writer's invited discussion was not included for unknown reasons.

The abstract of this writer's discussion reads as follows: "The hypotheses presented in JEREMIC's paper are biased by incorrect interpretations of subsidence caused by uncontrolled solution mining over many decades".

"It is shown in detailed discussions that the data referred to are inadequate; reliable published data, carefully collected over nearly a century and refined in recent publications, definitely contradict the presented hypotheses".

"JEREMIC's hypotheses and conclusions must not be applied to controlled solution mining in salt deposits".

The quoted reference to data collected over nearly a century refers to the subsidence data presented in Chapter 7 of this text.

6.2.4 Horizontal displacements

On Fig. 6-2, the amounts and the directions of measured horizontal displacements from 1956 to 1973 are shown by arrows.

STEVIĆ et al. (1979, p. 746) emphasize the maximum measured horizontal displacement of 3594 mm of benchmark 49.

Near benchmark 32, horizontal displacements of similar magnitude are shown in Fig. 6-2. It should be noticed that the horizontal displacements just south of the production well zone did not take place toward that zone, but away from it.

The arrows indicate horizontal displacements of the surface in two virtually opposite directions. Such displacements cannot be reconciled with the characteristics of a surface subsidence trough caused by salt extraction of any kind.

Particularly JEREMIC's (1975) hypotheses require the following corrections:

Apparently, the surface morphology must be taken into consideration. Fig. 6-3 shows the surface elevation at the northern boundary of the salt deposit approximately 50 m above the elevation at the southern boundary. The distance between the boundaries is approximately

500 m, so the slope is approximately 10 m over the distance of 100 m.

However, a similar slope is shown for the distance between the boreholes 1 and 4, although the surface is virtually horizontal between the boreholes 1 and 2, i.e., in an area with minimal horizontal displacements. In contrast, the area between the boreholes 3 and 4 (with a steeper-than-average slope) shows horizontal displacements of 150 - 200 mm/yr.

In other words, the horizontal displacements reflect the local morphology of the surface rather than effects of underground extraction. Down-slope movements of near-surface soil layers are described in numerous publications, but cannot be dealt with in this text. It is emphasized that the longterm horizontal displacements shown in Fig. 6-2 are rather small compared to the vertical displacements. Considering the mean error of 4 - 5 mm which might be involved in each of the measurements from 1956 to 1976, one might question the significance of horizontal displacements which cannot be reconciled with established subsidence characteristics.

As quoted in 6.2.3, JEREMIC (1975) postulates "shear rupture" of buildings in a zone surrounding the postulated sinkhole in the centre of the surface subsidence trough, and "extension rupture" in the next zone delineated by the zero contour line of vertical displacements. The writer shows a schematic section with the so-called sinkhole in its centre, and the shear zones between 70 and 20 cm of vertical displacement; the extension (tensile stress) zones extend far out.

The writer (l.c., p. 210) makes the statement that surface subsidence caused by conventional mining operations in bedded deposits is "very well explained" as "trough" subsidence; "unfortunately, there is no similar analysis for subsidence caused by solution mining". The latter statement makes no sense; it makes no difference to any overburden whether support is removed by natural salt solutioning, solution mining, or conventional mining. It is, of course, necessary to know the geometry of the excavations, the development of the excavations in time, and last not least the mechanical properties of the overburden. The latter condition cannot be met unless measured overburden subsidences allow certain inferences based on known geological conditions.

Usually, that condition is met only in well-established mining districts. The reader is referred to Chapter 7.

JEREMIC (1975, pp. 217-220) shows some photographs to support his hypotheses. His statements are partly quoted and commented on as follows.

(1) In the zone of shear deformation, "horizontal strains were the primary cause of the deformations. In this area the horizontal displacements produced both tensile and compressive strains. The compressive strains increased towards the zone of collapsing deformations".

Apparently, the writer refers to vertical displacements as compressive strains; this is shown in his "hypothetical model of the subsurface subsidence with stress field development" (l.c., p. 206).

(2) "Under this combination of stress, the surface objects were damaged by the shearing movements".

This writer is not sure of the meaning of the latter statement; the writer refers to strains as quoted under (1), and continues to refer to "this combination of stress".

(3) "Generally, it is considered that damage in this area is not very severe for buildings and that significant damage is only for railway tracks, pipes, etc.; this is probably true for subsidence caused by underground mining, but it is not for the subsidence caused by solution mining due to the intensive displacement".

This writer cannot consider vertical displacements of 20 to 70 cm as "intensive", particularly in cases where horizontal displacements are minimal and not even detectable in long-term measurements. As emphasized above, the method of removal of overburden support makes no difference to the subsidence characteristics in comparable cases.

JEREMIC (l.c., p. 218) describes extension rupture deformations as "the most intensive phenomena of the buildings damage in the Tuzla basin. The rupture deformations are caused by a tensile stress field. The tensile ruptures are generally vertical" as shown on a photograph. "These rupture deformations are more damaging than shear fracture and many buildings are semicollapsed".

The existence of a tensile stress field is not questioned. However, the origin of tensile stress on a plain surface cannot be explained if vertical displacements are absent.

The writer (l.c., p. 220) presents a "diagram of relationship between horizontal displacement and fracture opening on buildings"; "for horizontal (ground) displacements of 12 mm/m, the width of cracks is about 20 mm".

The writer contradicts the quoted statements in the following paragraph, elaborating as follows on "extension rupture zones": "Surface objects in most cases are without cracks due to the minimal horizontal displacement, but not only for this reason. For example, this area (Tuzla Town) mostly consists of residential houses whose sizes are up to 10 - 20 m, and deformations by subsidence cannot be as severe as for larger buildings".

Attempts to establish the postulated relationship between average horizontal displacement and width of tension fractures make no sense; clearly, the width of fractures associated with any given average ground displacement depends on how many fractures develop in a specific building; therefore, the construction characteristics of buildings must be taken into consideration. Certain types of construction of residential houses survive considerable horizontal and vertical displacements without damage.

In his conclusions, the writer (l.c., p. 222) again reverses his statements regarding damage to residential houses: in some areas of the town of Tuzla "where the salt horizon below had been extracted by solution mining for centuries, houses were built on the ground where subsidence was not noticed. However, those houses after several years were badly damaged by the unpredicted accelerated subsidence".

The writer uses the mis-interpreted subsidence in the Tuzla basin and those preceding the formation of the so-called sinkhole at Windsor in his attempts to develop a hypothesis on sinkhole formation. The subject matter is discussed in more detail in 6.3. It is emphasized here that OSMANAGIĆ and JAŠAREVIĆ (1977) do not mention a sinkhole in or near the town of Tuzla; however, their data show the development of rather deep surface subsidence troughs with typical characteristics, see Chapter 7.

6.2.5 Interpretations of the Tuzla subsidences

OSMANAGIĆ and JAŠAREVIĆ (1977) summarize the results of their research as shown in Fig. 6-4. The writers attribute the vertical displacements in zone 3 to variations in the groundwater level; "heavier rainfalls cause a rise of the groundwater level, decreasing the land subsidence, and vice versa" (l.c., p. 526). The variation range of the groundwater level over a year is given as 8 - 32 m.

The average drawdown in the production well zone was 30 m from 1956 to 1976. The writers attribute 183 mm (8%) of the average vertical subsidence to the 30-m drawdown and emphasize possible effects on buildings in areas where no subsidence due to salt extraction occurs.

The angle of draw of the overburden into the extraction zone was determined as 35° (l.c., p. 529). The writers announce stress and displacement measurements to be made in boreholes to check theoretical assumptions regarding the subsidence mechanism.

STEVIĆ et al. (1979) expect "pronounced arching" across the exploitation area; "the resulting stress ellipses...are generally rather extended" (l.c., p. 749). These postulates are based on erroneous assumptions and contradict the well-established fact that considerable surface damage due to localized subsidence took place. There appears no need for further discussion. The reader is referred to this writer's (BAAR, 1979) discussions of papers presented at the Third ISRM Congress on Rock Mechanics, Denver 1974.

Copies of these discussions were sent to the respective authors, including JAŠAREVIĆ (1974). If writers choose to ignore critical discussions, it just has to be accepted.

However, the hypothesis of pronounced arching across mined-out areas above which surface subsidence at considerable rates is in progress cannot be accepted, as outlined in detail in Chapters 2 and 3.

6.3 BRINEFIELD SUBSIDENCE AT WINDSOR, ONTARIO, CANADA

6.3.1 Published and unpublished reports mis-interpreted

The heading of this section was chosen in appreciation of a publication under the same title (TERZAGHI, 1970). The writer refers to several unpublished papers and reports dealing with the so-called sinkhole which formed in 1954 in the Sandwich brinefield south of Windsor.

Apparent misunderstanding and misinterpretation of TERZAGHI's data precipitated subsequent publications by writers who postulate the formation of a so-called chimney out of a salt solution cavity straight up to the surface. Surface collapse into the chimney is postulated to have caused the serious damage to buildings of the brine processing plant.

This writer considers hypotheses which postulate the formation of so-called chimneys untenable, as outlined in more detail in 6.5. The reason why TERZAGHI (1970) uses the term "sinkhole" is apparent from the following quotation (l.c., p. 298): "Unlike many of the surface depressions associated with brine extraction, the Windsor depression, locally called the sinkhole, was centered neither about a single well nor about a group of wells. It appears rather to be the result of subsidence of rock strata into extensive cavities in underlying salt deposits".

The writer clearly dismisses the hypothesis of chimney formation and surface cratering. However, the use of the local term "sinkhole" throughout her publication may have confused some writers who apparently are not familiar with overburden subsidence characteristics, see Chapter 7.

In view of the controversial nature of the topic, some of TERZAGHI's statements are quoted. This writer's comments are principally based on written communications with PIPER (1974) whose classifying notes are acknowledged.

(1) "In 1948, settlement cracks were noticed in buildings within the Sandwich brinefield. Thereupon, about 85 reference points were established on structures in the area. Changes in elevation of these points were measured at yearly intervals".

Fig. 6-8 (TERZAGHI, 1970) shows some of the reference points in

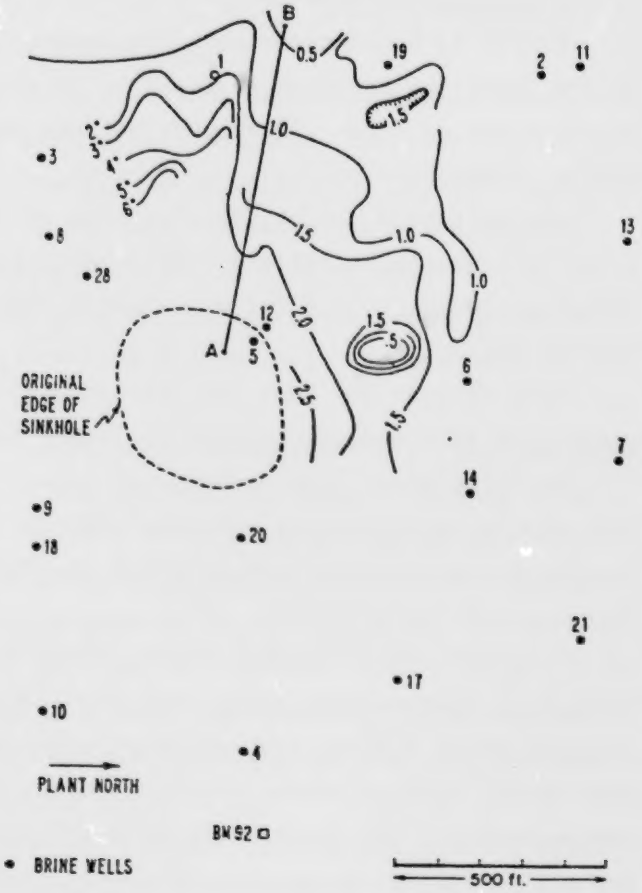


Figure 6-8: Subsidence at Windsor, Ontario, October 1948 to October 1950 (from TERZAGHI, 1970, Fig. 2).

the Sandwich brinefield.

The fact that settlement cracks appear in buildings leaves no doubt of considerable lateral displacements near the surface, see 6.2. Vertical displacements of several metres do not necessarily cause damage if the subsidence characteristics, see Fig. 7-1, are taken into appropriate consideration in the planning of a brinefield.

Cracks in buildings within the Sandwich brinefield formed long before 1948; the cracks were repaired, and repaired cracks had new cracks crossing them. These observations were made in 1948 (PIPER, 1974 written communication).

The reference points for elevation surveys were established on structures in the brinefield. This means that changes in elevations of reference points are not necessarily indicative of general surface subsidence.

Some changes may just indicate lateral displacement of unconsolidated soil from underneath heavily loaded foundations of buildings.

In large areas, the groundwater level in the brinefield was nearly identical with the ground surface. The Detroit river, flowing approximately N-S near point B of Fig. 6-8, provided for unlimited water recharge.

(2) TERZAGHI (1970, p. 305) discounts "a flow of clay" over near-horizontal distances of about 1000 feet (304.8 m) toward the so-called sinkhole as "a process without known precedent". However, lateral flow of wet unconsolidated soil over short distances is certainly not unprecedented. The foundations of heavy buildings may just sink into wet soil; related changes in the elevation of reference points must not be attributed to the brining operations.

If well casings were used as reference points, these points probably indicate vertical displacements of the bedrock surface.

(3) "Levels were carried out with ordinary rather than with precision instruments; the elevation of a given reference point at the time of any one survey may have been determined with an error not exceeding one-half inch. Variations of this order of magnitude in successive readings are probably not significant".

In other words: the possible accumulation of errors over several years makes any contouring of vertical surface displacements questionable unless the possible error limit is clearly exceeded.

(4) "By the end of the second year (October, 1950) settlement observations indicated that a bowl-shaped depression was developing. As shown in Fig. 6-8, maximum observed subsidence in 1950 had taken place in an area several hundred feet west of the site of the future sinkhole".

(5) Fig. 6-9 shows that "in the following years (1951 through 1953) settlement increased at an accelerating pace".

The writer elaborates as follows: "The maximum observed subsidence in 1950 had taken place in an area several hundred feet west of the site of the future sinkhole. The reference points in this area were not again surveyed until 1954, and it is therefore not known whether this area continued to experience the maximum rate of subsidence".

(6) According to Fig. 6-8, the area north of the developing "sinkhole" subsided by only about 2.5 in. from 1948-1950, i.e., at the rate of 1.25 in./yr.

Fig. 6-10 shows over 16 inches of total subsidence of the same area in 1953, i.e., an additional 14 inches over the three following years. The average subsidence rate from 1950 to 1953 calculates as 4.7 in./yr.

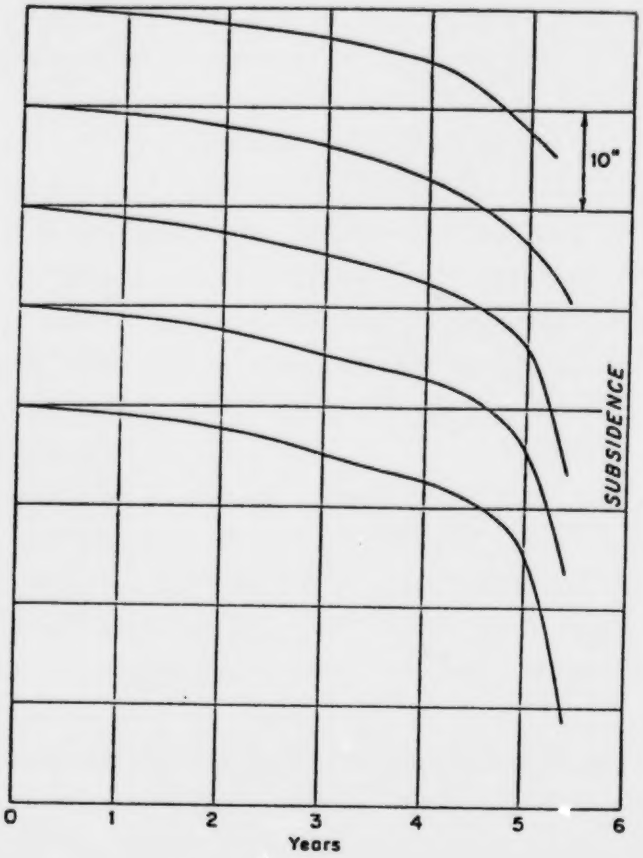
These data clearly indicate the considerable acceleration of the overburden settlement in the area north of the future "sinkhole" since 1948.

(7) The 1950 contour map, Fig. 6-8 needs correction of some apparent errors in contouring. However, without knowledge of the original data, the required corrections cannot be made.

(8) Fig. 6-10 shows why successive profiles through the western part of the brinefield fail to indicate the apparent shift of the maximum subsidence rate toward the future "sinkhole: over most of its length, the profile line A-B, Fig. 6-8, runs approximately parallel to the 12-in. contour line; the area of more than 6 inches of surface subsidence is not touched.

For this reason the successive profiles shown as Fig. 6-11 are incorrect and misleading.

(9) NIETO-PESCETTO and HENDRON (1977, p. 35) show the same profile as "successive profiles through the westerly portion of the area of localized subsidence at Windsor" (l.c., p. 34). This is another error:



TIME-SUBSIDENCE CURVES

Figure 6-9: Accelerated subsidence of reference points near sinkhole (from TERZAGHI, 1970, Fig. 3).

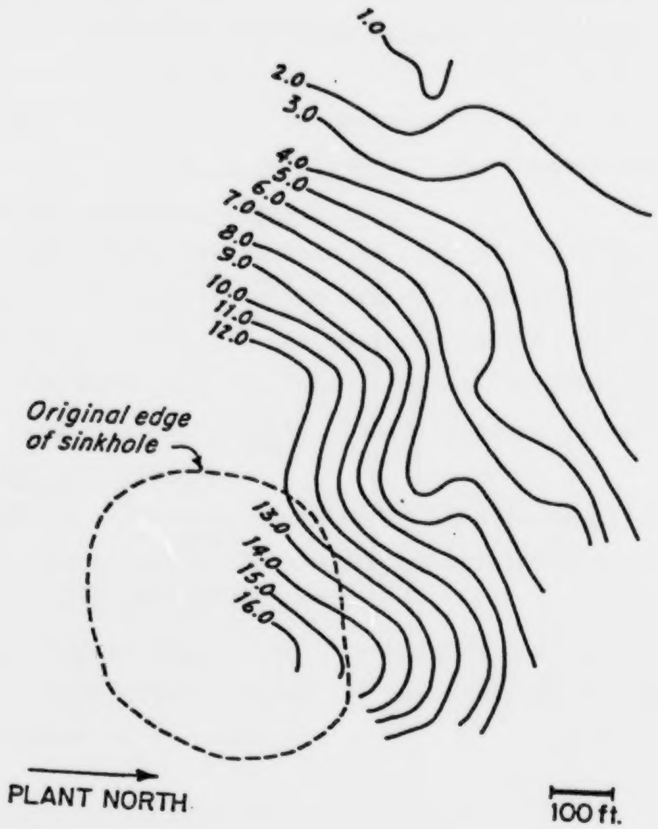


Figure 6-10: Total subsidence in inches, measured from October 1948 to October 1953 (from TERZAGHI, 1970, Fig. 4).

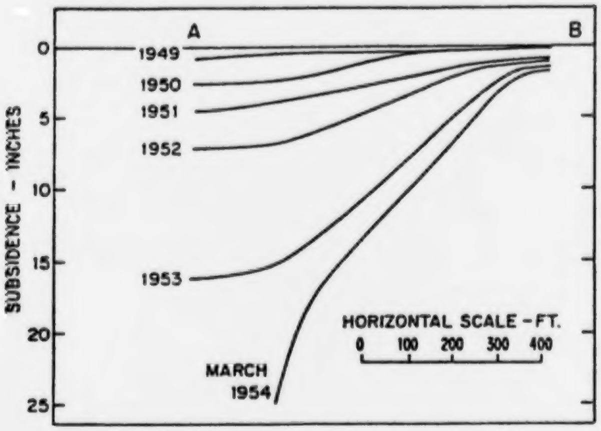


Figure 6-11: Successive subsidence profiles, 1949 to 1954, along section A-B of Fig. 6-8 (from TERZAGHI, 1970, Fig. 5).

the writers distinguish between "downwarping or generalized subsidence" and "localized subsidence" which is supposed to develop "much greater surface gradients"; the successive profiles cover the area of downwarping from its centre to the Detroit river.

However, in the area of localized subsidence near the future "sinkhole" much smaller surface gradients developed because of decreasing subsidence rates (decelerating subsidence).

This writer considers the shift of the maximum subsidence rate toward the future "sinkhole" as most significant in the interpretation of the mechanism of the subsidence process.

It is emphasized that the "original edge of sinkhole" in Fig. 6-8 and 6-10 was not roughly circular; it rather demonstrates two preferred directions near the so-called sinkhole. As mentioned above, the 12-in. contour line runs west for more than 200 feet from the "original edge of sinkhole"; then it turns abruptly south. Similar abrupt changes are shown north of the so-called sinkhole.

Fig. 6-12, showing the difference in rates of subsidence per year for 1949 and 1953, also demonstrates the continuing acceleration of the localized subsidence west of the future sinkhole.

In order to enable further discussion of published and unpublished reports which contradict each other frequently, some data on the geological conditions are given as follows.

6.3.2 Geology of the Sandwich brinefield

The general geology of the Windsor/Detroit area is discussed in 4.3.1. Fig. 4-3 shows the stratigraphic section found at both sides of the Detroit river and on some islands with solution mining operations. TERZAGHI (1970) uses a different terminology, see Fig. 6-13.

According to TERZAGHI (1970, references not included), "the Sandwich brine field is underlain by unconsolidated Pleistocene deposits consisting chiefly of stiff clay and silt...Locally, the clay rests on lenses of sand or gravel with a maximum thickness of a few feet. Well logs indicate that the total thickness of the unconsolidated material ranges between 85 and 104 feet within the area of gradual subsidence prior to the formation of the sinkhole". "A thickness in excess of

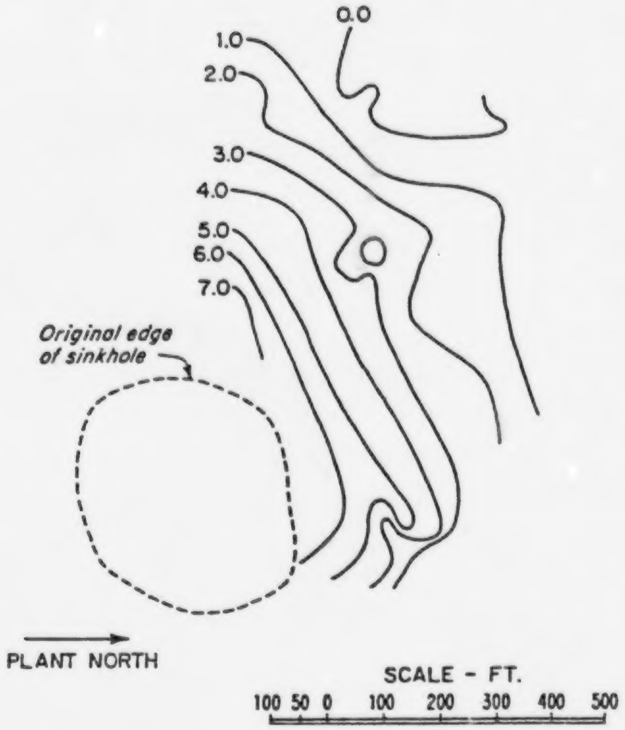


Figure 6-12: Differences in rates of subsidence in 1953 and 1949, inches per year (from TERZAGHI, 1970, Fig. 6).

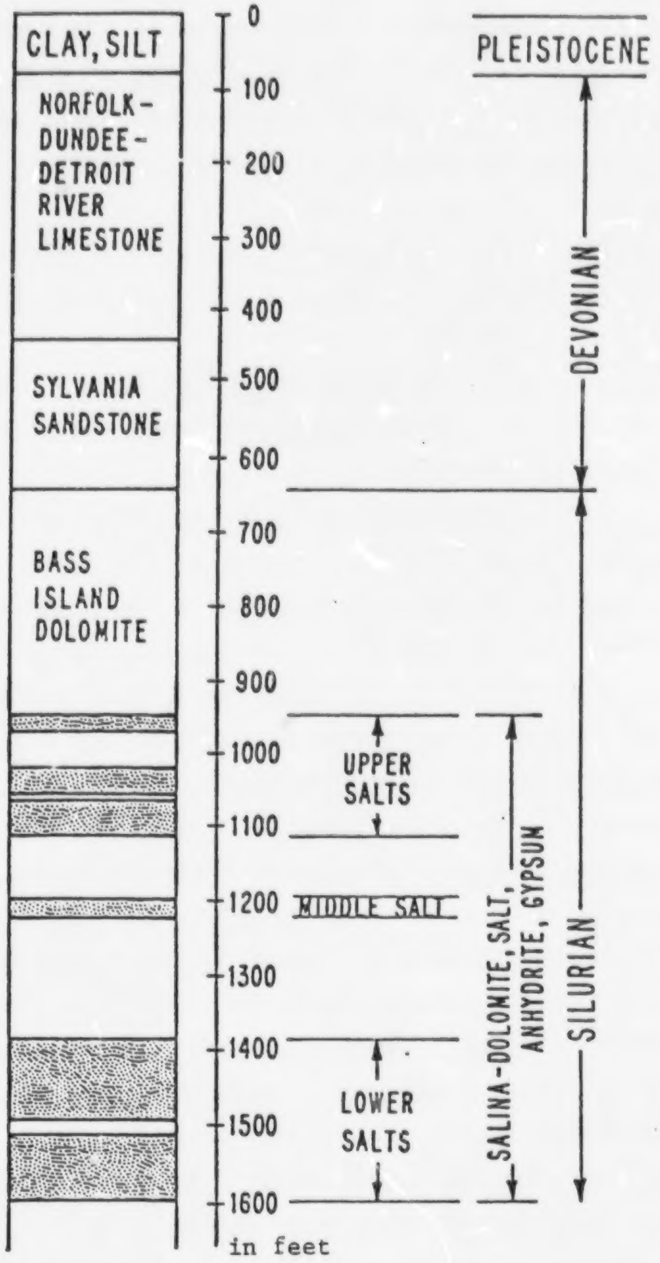


Figure 6-13: Typical geological section, Sandwich brine field (after TERZAGHI, 1970, Fig. 1).

99 feet was encountered in only two of the twenty wells for which data are available, and the log of only one of them indicates a thickness of less than 91 feet. These data suggest that the thickness of the clay underlying the subsiding area, was, with minor exceptions, between 91 and 99 feet."

"The Pleistocene sediments are underlain by sedimentary rocks of Devonian and Silurian age. As shown in Fig. 6-13, the uppermost part of this sedimentary series consists of several hundred feet of...a predominantly brown limestone 335 ro 350 feet thick. Large yields of water, and mud losses during drilling, indicate it is extensively jointed and fractured."

This writer wishes to emphasize here that large yields of water, and mud losses, clearly indicate intensive karstification as shown in previously presented case histories, see Chapter 4. The subject matter is discussed in more detail in 6.3.3.

TERZAGHI (1970) continues her descriptions as follows: The limestone "rests on sandstone belonging to the Sylvania Formation of Devonian age...The sandstone is usually in two benches split by gray and brown limestone. The three units total 174-200 feet (53.33-61 m) in thickness. Cementation in the Sylvania is highly variable; some beds are well cemented with carbonate or silica and others are very loose."

"Carbonate strata of Upper Silurian age, commonly about 300 feet in total thickness, underlie the Sylvania". The carbonates belong to a dolomite formation "encountered in brine wells in the Detroit area. In that region, the uppermost two hundred feet of the formation is reported to be sound, strong and competent, and capable of bridging cavities with a span of several hundred feet without any indications of stoping".

"This observation indicates that the joints are in general far apart, the blocks between joints well interlocked, and the bond across bedding planes farily strong".

"The uppermost evaporite bed was commonly encountered in the Sandwich wells at depths ranging between 975 and 1000 feet". The writer apparently refers to the uppermost salt bed. "This bed, together with the underlying approximately 800 feet of dolomite, shale, gypsum, anhydrite and salt, has been referred to the Salina Formation of

Silurian age."

"The uppermost bed of salt is generally 10 - 30 feet (3.05 - 9.14 m) thick. Separated from this bed by a few tens of feet of carbonate rock, the underlying salt consists of one or more strata with an aggregate thickness of eighty to one hundred feet in the Sandwich area. Together these beds constitute the "Upper Salt." At a depth of about 1100 feet, the base of the Upper Salt rests on rock called limestone by the drillers."

"At depths between 1200 and 1250 feet, one or more strata of salt were encountered in many of the wells. Unnamed in brine field practice, they will herein be called "Middle Salt." These thin, discontinuous strata cannot have made a notable contribution to the total salt production, but rockfalls associated with them seem to have caused a disproportionate fraction of the tubing and casing breaks experienced during the operation of the brine field."

"Failure to distinguish between rockfalls in the Middle Salt and those in the Upper Salt has apparently led some observers to overestimate the relative amounts of solution in the Upper Salt. In order to avoid such an overestimate, it appears useful to recognize the separate existence of the Middle Salt." "During drilling of some of the wells, cavities with a maximum height of 20 feet were encountered in both the Upper and the Middle Salts. Some, possibly all, of these were of natural origin." "The Lower Salt consists of two beds separated, according to the well logs, by a few feet of limestone. Occurring between depths of about 1400 and 1600 feet, they have an aggregate thickness close to 200 feet."

"Formations penetrated by brine wells of the area have undergone little or no deformation. "Regional dips vary from slightly west of north to northwest. They average 60 to 70 feet per mile and rarely exceed 100 feet to the mile."

Regarding the quoted descriptions by TERZAGHI (1970), it must be emphasized with PIPER (1978, written communication): the top strata of the limestone formation ("BASS ISLAND DOLOMITE") are weathered; the topography of their surface shows relief (stream channels, etc.) ranging to depths of 100 feet. These apparent karst features contain sulphurous water under artesian pressure and require the following more detailed discussion.

6.3.3 The significance of karst features

With the exception of LANDES and PIPER (1972), all other writers dealing with brinefield subsidences in the Windsor-Detroit area fail to consider the significance of karst features in the development of surface subsidence troughs. Karstification of the bedrock underneath the unconsolidated near-surface sediments in the Sandwich brinefield appears to be the most significant geological phenomenon.

Karstification must be considered in any attempt to interpret the mechanism of overburden settlement in the Sandwich brinefield, or in any other area where overburden subsidence results in the formation of real or so-called sinkholes.

Some quotations from LANDES and PIPER (1972) are discussed here to elucidate the significance of hidden karst phenomena.

According to the writers (l.c., p. 42), "carbonate rocks (limestone, dolomite), although less soluble than gypsum and especially salt", are dissolved by "ground waters with abundant carbon dioxide in solution".

"Furthermore, limestone is a very abundant rock at and near the surface in many parts of the world, so limestone sinkholes are plentiful, whereas salt and gypsum sinkholes are much fewer."

This statement is inconsistent with the relative solubilities of carbonates, sulphates, and salt rocks. The reader is referred to Chapter 4.

Referring to examples of natural sinkholes, LANDES and PIPER (1972) note: "In many limestone areas the surface is so pockmarked with sinks that neither a straight road nor agricultural pursuits are possible. Where the rainfall is such that the water table is shallow each sinkhole contains a lake. The physiographic term to describe such topography is "karst".

"Many limestone floored parts of the eastern United States, especially Kentucky and Florida are karstic. Actually any area with limestone at or near the surface is subject to sinkholing."

The writers (l.c., pp. 37-44) define related depressions on the earth's surface as follows "completely surrounded by higher ground." Their study "is primarily concerned with depressions brought about by sagging or collapse of the surface due to man's activity. The collapse craters are referred to as sinkholes. Just as for every man-made lake there are many thousands of lakes resulting from natural geological processes, so every man-created sinkhole is overmatched by many thousands of natural sinkholes".

According to this philosophy, the writers divide their discussion "of sinkhole and other collapse features into two categories: those caused by man's activity, and those created by acts of God. In terms of timing, the man-made features are obviously confined to recent history; and the actual collapsing has in many instances been witnessed. On the contrary, most act of God collapsing is prehistoric. This is not surprising, when you recall that all historic time is but a split second of geologic time".

These hypotheses may be acceptable for limestone areas referred to by the writers; however, in areas where evaporite sequences with salt are present near the surface, the following relationships must be taken into consideration:

(1) The solubility of $CaSO_4$ is much higher than that of carbonates, particularly in salt solutions. As a consequence, the karstification of gypsum/anhydrite needs less time and tends to be more intensive.

However, karstification is restricted to areas of present or ancient groundwater flow; it can penetrate only to certain depths below the surface.

(2) Salt sequences are not karstified when dissolved by groundwater, see 4.1. "Saline karst" is restricted to areas where salt deposits are attacked at or above the surface by rainwater, while the groundwater table may exist at much greater depths.

Such conditions may have developed at any time since the original salt deposition; as a matter of fact, Devonian karst features including channels leading to sinkholes are abundant in the Prairie Evaporites of Saskatchewan, see Fig. I/2-11.

LANDES and PIPER (1972) appear to assume intensive karstification throughout the Windsor-Detroit area; the karst features are covered and hidden by insoluble Pleistocene sediments. When saturated with water, such sediments are very mobile; they may be displaced into karst cavities in the underground, or into man-made salt solution cavities when overburden settlements due to solution mining take place.

Such displacements of mobile material are not predictable, unless the location and the volume of karst cavities or man-made cavities are known. That indispensable knowledge is difficult to obtain; it was definitely not available in the Sandwich brinefield.

Mobilization of near-surface sediments may be attributed to the formation of the so-called sinkhole which was definitely not a surface collapse crater of the type referred to by LANDES and PIPER (1972). These writers, like TERZAGHI (1970), place particular emphasis on the fact that "the depression has been backfilled, a railroad siding traversing the area rebuilt, and operations resumed". The latter statement refers to the brine processing plant; the brining operations in the Sandwich field were terminated when the so-called sinkhole formed in 1954.

LANDES and PIPER (1972) show two photographs which were taken from the same position in 1954 and in 1971, respectively. "The 1954 photo shows the Windsor sinkhole shortly after its occurrence. The 1971 photo shows the site after restoration to use by backfilling the hole and construction of railroad tracks".

The large plant building seen on both photographs apparently suffered little, if any damage from the postulated formation of a chimney down to the salt cavities; the building stands apparently undamaged perhaps 15 m from the edge of the so-called sinkhole.

The writers (l.c., p. 39) emphasize that "a main generating station of the Canadian Hydropower System is located nearby and was undisturbed by this event".

As already stated at the end of 6.3.1 and shown in 3.2, real surface craters caused by salt extraction re-appear when back-filled; some developed into deep lakes, the deptn of which equals the depth to the extracted salt deposits less the thickness of the disturbed overburden.

It cannot be questioned that the depression in the Sandwich brinefield was brought about by sagging of the surface due to man's activity; on the contrary, brine pumping over decades must result in surface depression if the span of the brinefield exceeds considerably the depth to the level of salt dissolution.

However, the formation of a chimney vertically up from the level of salt extraction appears unacceptable to this writer.

In order to enable an adequate discussion of the subsidence data available for the Sandwich brinefield, it appears indicated to present the questioned hypothesis of chimneying in the following.

6.3.4 Postulated mechanism of sinkhole formation

According to LANDES and PIPER (1972, p. 39), "The Solution Mining Research Institute (SMRI) has undertaken an investigation to attempt to determine the mechanism which operates in the formation of a sinkhole related to salt production."

Some of the published studies are discussed in more detail in the following. The writers (l.c.) summarize their study as follows: "It is generally recognized that salt extraction by the classical method of well operation results in subsidence of the surface either as downwarp, or in some instances as a sinkhole. Only a few of the better-known examples are listed here. These are cited to illustrate that subsidences are widespread, but upon termination of the activity are relatively easily accomodated disruptions to the environment. It is important to note that surface effects are confined to the area overlying the salt cavities - neighboring areas are not involved."

The surface subsidence data presented and discussed in this text make it impossible to agree with the quoted summary. Particular disagreement is expressed regarding statements concerning "collapsed underground mines" which read as follows:

"Mining, near the surface and mostly of coal, has been followed by the partial or complete abandonment of overlying communities, especially in eastern Pennsylvania and western Wyoming, due to slumping of the surface into the underlying workings. Hopefully, the greater depth of current mines, and the public insistence that adequate pillars of coal or ore be left intact or that openings be backfilled, will prevent such occurrences in the future".

These statements may apply to shallow mines in the cited areas, but must not be generalized, as they disregard the serious effects of brining operations on the groundwater regime.

In conventional mining of salt and potash greater depths inevitably cause more stress relief creep into mine openings, as shown in Vol. I.

No matter how much ore is left intact in pillars - up to 70% in some Canadian potash mines at depths exceeding 1000 m - surface subsidence cannot be prevented above mined-out areas with sufficient spans. The inevitable overburden subsidence can and must be controlled by adequate support pillars, or by other means where feasible; one possibility is to take advantage of the roof caving characteristics as shown in Chapter 8.

The successful application of mining methods with intentional roof caving cannot be reconciled with hypotheses developed in attempts "to determine the mechanism which operates in the formation of a sinkhole related to salt production".

LANDES and PIPER (1972) offer two entirely different hypotheses on sinkhole formation.

One hypothesis is quoted as follows (l.c., p. 46): "Some concern has been expressed that the collapsing cavern roofs, with chimney-like connections with the surface, would permit the mixing of the saturated cavern brines with higher waters. In our opinion this is unlikely, for even if the collapse material filling the chimneys is permeable, the saturated brine would have difficulty penetrating potable water because of the 20 per cent greater density of the brine. By our conception of sinkhole formation wherein roof rock falls to the cavity floor and the cavity thus grows upward by stoping to form a chimney, no decrease in volumne occurs. Roof rock drops to the floor, changing place, but cavity volume does not diminish".

Exactly the opposite is stated as follows (l.c., p. 17): "As dissolving progresses, insoluble beds are undermined and eventually collapse. This collapse occurs due to (1) removal of the underlying support, (2) dissolution of the soluble minerals that may constitute the matrix of the layer, and (3) inherent structural incompetence...

The collapsed material accumulates in the cavity as rubble or debris, usually stacked in a random fashion, and the resulting increase in volume is known as bulking".

The "mechanism known as bulking" is described in more detail as follows (l.c., p. 21): "Operation of conventional wells is recognized to cause undercutting of large areas at the top of the salt beds beneath the overlying rock that constitutes the roof of the cavity. Early indications of undercutting were obtained when wells were found to have coalesced at the top, permitting essentially fresh water to pass from one well to another; because of the low gravity of the produced brine, it was assumed that this connection was across the roof or even in the overlying rock through bed partings. Additionally, some wells drilled near conventional wells encountered cavities at the top of the salt bed".

"Another result of the operation of conventional wells was progressive caving or stoping, to use a mining term, of the overlying layered rocks surrounding the well casing. This was determined by collapse or loss of casing, and the introduction of the wireline caliper device showed loss of roof rock that had taken place in the interval between logging runs. Collapsed material was found to be accumulating on the cavity floor by either sounding line or measurement of the depth at which drilling tools or tubing hit the top of the rubble pile".

"In many instances the increase in volume of the rubble, due to random stacking of collapsed material, caused the rubble pile to grow near to or up to the new cavity roof. This mechanism, known as bulking, is considered to have filled the void in many places, and restored support of the overlying rock, thereby preventing further collapse".

It is re-emphasized that approximately 50% of the required overburden support is provided by the brines in solution-mined cavities.

On the basis of observations in numerous potash mines, this writer considers the quoted description of the "mechanism known as bulking" as fully acceptable, as discussed in detail in 5.3.1.

Consequently, the contrary concept of roof rock dropping to the floor in a chimney, changing place, but not diminishing the volume of the cavity is considered untenable. The reader is referred to 6.1.

The chimney hypothesis is considered particularly questionable in areas where karst features exist in evaporites other than salt above cavities in salt sequences, no matter how the cavities are created. Unconsolidated, water-saturated sediments may flow into underlying cavities as soon as roof failure, working its way up from the cavities, creates suitable connections.

The best known example to elucidate the mechanism of flow of unconsolidated material appears to be the flooding of the Cominco potash mine near Saskatoon (PRUGGER, 1979b). In 1970, during routine grouting in one shaft, the water-bearing sands and silts of the Blairemore formation at the depth from 517 to 633 m below surface were accidentally tapped by a borehole. The shaft may be considered as a chimney connecting the mine workings with the unconsolidated formation.

It took only a few days until the mine workings were filled with water, fine sand, and mud; 15000 m^3 of solid material had to be removed before underground clean-up could begin after the break had been sealed, and the brines had been pumped out of the mine workings.

As outlined previously, LANDES and PIPER (1972) assume extensive karst features in the non-salt evaporites underneath the so-called Windsor sinkhole. Needless to say that unconsolidated, water-saturated near-surface sediments may flow through karst cavities into underlying salt cavities as soon as such karst features are tapped by successive roof failure. The writer emphasize that torrential rains fell prior to the formation of the so-called sinkhole.

Karstification in areas affected by block faulting tends to produce linear karst cavities, see 4.4.2 for examples. However, neither TERZAGHI (1970) nor NIETO-PESCETTO and HENDRON (1977) mention any possible hidden karst features underneath the Windsor depression.

This writer also cannot agree with statements (NIETO-PESCETTO and HENDRON, 1977) regarding "the state of the art in predicting the point at which brining operations should be stopped or modified in order to prevent the formation of sinkholes".

The writer's objective is "to define guidelines which could be used to indicate sufficiently in advance when a potentially dangerous situation is imminent"; this cannot be achieved unless hypothetical misconceptions of chimneying are dropped, and appropriate attention is paid to subsidence characteristics, see Chapter 7.

"Surveys of surface subsidence are or could be used at all brine fields where the operators are seriously attempting to control subsidence", as the writers put it (l.c., p. 4). This statement definitely holds true for what the writers term "downwarping or generalized subsidence".

Regarding "localized subsidence with or without attendant sinkhole formation", the writers refer to an unpublished paper (PECK, 1954); the cover of their publication "pays respect to Dr. PECK and offers his rendition of the sinkhole mechanism as an example. The sketch shows the salt cavity, the chimney in the overlying rocks (stoped area) and the resulting surface crater.

The subsidence data discussed in 6.3.1 and the facts presented in the following text cannot be reconciled with the postulated sinkhole mechanism.

6.3.5 Brine extraction history

According to TERZAGHI (1970), "the first brine well was drilled in the Sandwich field in 1902, but relatively intensive development did not begin until 1922. Between that year and 1953, 25 wells were drilled to a depth of about 1600 feet, to the base of the Lower Salt. The casing appears generally to have extended to a depth between 1237 and 1290 feet, that is, below the Middle Salt, and the tubing to the bottom of the well," see Fig. 6-13.

"All of the wells drilled before 1928, and most of those drilled later, were operated initially as water-forcing wells. Sooner or later, most of the wells became connected through solution channels to one or more of the others, and finally to a "general cavity," which, according to Dr. BAYS, was in the Lower Salt."

"The available data concerning the design, construction, and operation of the wells indicates that brine was drawn from all three salt horizons. With the exception of three wells drilled prior to 1918, all were designed to extract brine from the Lower Salt. The high incidence of recorded rock falls at or below the level of the top of this horizon

(30 out of a total of 50) indicates that the 200-foot thick Lower Salt was, as intended, a major source of brine. In addition, an unknown but doubtless large quantity of brine must have been derived from the Middle and Upper Salts, owing to the introduction of water into these beds through defective well casings and around inadequate packers."

"In view of the fact that the total thickness of the source beds underlying the brine field is about 300 feet, it is evident that the total height of cavities underlying the field may have been unusally large. However, because of impurities in the salt and the irregularities of the solution process, the total height of cavities beneath any one point on the surface was doubtless much less than the possible maximum of 300 feet."

"The total volume of the cavities due to brine production at the Sandwich field can be roughly estimated from information concerning production. According to BAYS, the total production of the Sandwich field was about 71 million cubic feet. He concluded that the quantity of injection water greatly exceeded that of the brine recovered, and he estimated that more than 150 million cubic feet of salt had been removed from the deposits underlying the plant area when production ceased in February, 1954."

"If salt extraction had produced a single large cavity in the form of an inverted cone with a diameter of 2000 feet, instead of a considerable number of originally separate but ultimately connected morning-glory-shaped cavities, the cavity would have a maximum height of 150 feet."

"The well records given in BAYS' report provide scant information regarding the real shape, size, and location of individual cavities or of the "general cavity" to which most of the wells ultimately became connected. The earliest wells so connected were in a centrally located zone extending from the northerly side of the brine field to the southerly side (wells no. 7, 6, 5, and 9). It would not be surprising if maximum solution had taken place in those parts of the salt beds that underlie this zone. The area of maximum surface subsidence is located in the southerly part of this zone."

Important pieces of available information are to be added to the quoted history of the Sandwich brinefield.

According to PIPER (1954, written communication, referring to unpublished reports), the intensive exploitation of the brinefield included the pulling of well casings. Groundwater with unlimited recharge from the Detroit river had uninhibited and uncontrolled access to all salt beds. Some of the cavities "of natural origin" mentioned in 6.3.2 may in fact be solution channels.

The writer (l.c., p. 9) emphasizes that "two drilling projects were conducted in the area of the plants previous to the establishment of extensive brine-production facilities, which may prove to have a bearing on the present condition."

In 1870 "the Sandwich Petroleum Company drilled an exploratory hole for oil which was successful only in tapping an artesian head of sulphur water. The hole was drilled to the upper contact of the No.4 salt, a depth of about 1400 feet (425.7 m), and was abandoned without plugging. The flow of sulphur water was the basis of a fluorishing health resort".

"In 1914, a brine well was drilled to the base of the No.4 salt by the Canadian Alkali Company. The well was abandoned without plugging when the company failed. It is not known whether these wells have coalesced with the general gallery - if so, an uncontrolled connection exists between the No.4 and No.2 salts".

"The Saginaw Salt and Lumber Company produced evaporated salt on the site of the present Canadian Salt Company...The company failed in 1909. No record of the location of the wells is available although the salt was reported to have been produced from the No.2 formation."

"The Canadian Salt Company, a predecessor to the present companies, started operations in 1911, producing chlorine and caustic soda by electrolysis, and dry salt by evaporation using waste steam. Sixteen wells were drilled which bear the first sixteen well numbers of the present brine field...The wells were drilled and tubed to the bottom of the No.4 salt although the casing was set on packers at a much higher elevation".

"The wells caved-in the formations above the lower salt and some were plugged after a life of a few years; others existed for many years and were progressively operated at higher elevations as tubing failures forced higher settings. Casings were not cemented and frequently failed due to collapse or corrosion; wells were put back into service with a minimum of casing repair. As a result, cross-connections in the upper salt formations were created and developed uncontrolled."

"The Canadian Salt Company was absorbed by CIL in 1928, with a reported production during the period of its existence of 408,850 tons of salt as brine and 352,00 tons of evaporated salt".

"Under CIL, brine was produced from the original field and new wells were added to replace those plugged and to increase production. Many were drilled directly into the main gallery of the original 16 wells under the plant site, and others were drilled in a new field to the east of the plant. Most of the original wells have been plugged and deep well pump installations made in a few wells which sustain the plant demand. In recent years well No. 19 at the river has been used as a water inlet, and pumps installed in wells No. 13 and 15. Individual wells in the new field were pressure-operated; some are still washing in".

"Throughout its history, No. 19 well has failed at various depths; at one time the casing was broken in the formations above the salt sections and was considered impossible to repair. The casing was 'picked up' and water injection continued. This situation would permit access of the water to any of the salt strata without control. Free vertical cross-connections between the salt sections must exist in most of the wells, as casing cementing was undertaken only recently, with no returned (cement) reported, and as mentioned above, many holes drilled in the area were never plugged".

"Water injected at well No. 19 has been estimated to have been between 1.5 to 2.5 times the volume of brine extracted, indicating loss of vast quantities of salt and undermining of large areas of the plant area. Production by CIL to 1946 is reported as 56 million cubic feet (1.59 million m^3) of salt".

"The estimated size of the cavity and the excess water injected indicate that cross-connection may exist with the Solvay wells on Zug Island" (approximately 2700 feet (823 m) across the river).

"With this history of uncontrolled solution, vast quantities of unrecovered injection water, and operation of wells not sealed between formations, it is little wonder that subsidence should be evidenced in the plants. Examples may be seen of tension cracks in foundations which have been patched in the past and which have opened again along the same lines. Other manifestations of settlement are reports over the past five or ten years of broken pipelines and sewers which failed to flow".

Nothing has to be added to the quoted appraisal of the uncontrolled solutioning practices in the Sandwich brinefield. The writer emphasizes that the elevation readings taken in 1948, when compared with the design elevations, "indicated as much as several feet of settlement to that date. Subsequent annual readings showed several inches per year on many of the points." A contour map indicated the centre of the surface subsidence trough.

"Time vs. settlement plots of several selected points...reveal a considerable acceleration in the rate of subsidence in the years 1952-53".

"No interpretation was made of the information revealed by the contour map to localize the phenomenon. The establishment and observation of reference points in areas without structures at that early period would have yielded valuable information as to the closure of the contours, and would have precisely outlined the area of the sinkholes".

This reference to the area of the sinkholes, i.e., to more than one sinkhole, is not a typing error. Elsewhere in his report, the writer refers to "events of a similar nature, but to a lesser degree, (which) have been observed at the site and recorded in the past".

6.3.6 Formation of "sinkhole"

TERZAGHI (1970) gives the following account of events during the actual formation of the "sinkhole".

"On February 19, 1954, several months after the fifth annual survey of the reference points, an alarming series of events took place at the site of the plant. The following account of these events is based on eye-witness reports".

"The first precursors of trouble consisted in rumbling noises and minor vibrations noted between 8 a.m. and 9 a.m. These became more severe after 9 a.m. Next, distortions and leakage of various water and steam lines were observed, and by 10:30 a.m. it was apparent that a depression was forming in the originally nearly level surface of the ground".

About noon, the depression began to fill with water from a nearby swamp and later from a ruptured water main and a brine line. Another source of water was a short-lived jet of water spurting from a fissure which had opened in the ground within the depression".

"At about 1:45 p.m., a rapid subsidence, amounting to approximately three feet, took place around one side of the rim of the depression. This event was accompanied by the appearance of a jet of water about four feet high, issuing from the fissure along which subsidence had taken place. In the early afternoon, additional jets or "fountains" developed at points which eventually became submerged. One of the largest of these formed a wall of water four feet in height and 75 feet long. In general, individual jets remained active for periods of two to five minutes. The water which thus spurted from the ground appeared black and had a sulphurous odor".

"By mid-afternoon, movement had virtually ceased".

"There was a water-filled depression, "the sinkhole," roughly elliptical in shape, with a maximum diameter of nearly 500 feet and a maximum depth in excess of 25 feet. The pond occupied the center of a larger bowl-shaped depression with a radius of about 1000 feet. Many of the plant buildings were damaged beyond repair.

Brine production at the Sandwich field was permanently discontinued after the sinkhole had formed.

In the months following the formation of the sinkhole, the pond was pumped out and the depression was filled with sand and gravel.

TERZAGHI's (1970) quoted account is to be compared with the following "summary of events which took place during the day of actual sinking of the surface" prepared by PIPER (1954, written communication).

The writer stresses that "this compilation is based on information derived from untrained observers who were not thinking in terms of subsidence, but of major catastrophe, as indicated by references to "earth fault" and inqiries to the seismological observation stations in this area, and thus should be weighed with that in mind".

"9:00 a.m. - Sounds and shocks similar to blasting or bumping of railroad cars. No great concern other than inquiry as to the source of blasting...Noises and shocks recurring at approximately 15-minute intervals."

"10:15 a.m. - Breaking pipelines, i.e., steam, brine, chlorine, and an overhead boiler cinder discharge line, culminated in the breaking of the high-pressure water main...New cracks noted in the foundation of the chlorine pumping station. Workers evacuated from the plant and emergency measures taken...Welders reported that the brine main would pull apart before they could weld it together; the repair operation was finally abandoned. Some settlement observed in a railroad track...and in an overhead pipeline".

"Noon - Definite area of settlement defined on the surface. Water reported as spouting five to six feet from fissures. Brine well No. 28, plugged above the salt section, emitted water. Water from these sources was high in hydrogen sulphide but no salt was reported".

"1:00 p.m. - Settlement of the chlorine liquefaction quite noticeable; crack in floor about one foot wide. Warehouse directly over the sink area was seen to settle by measurable amounts. Water flooding the depression from broken mains and run-off from torrential rains in the days preceding."

"2:15 p.m. - One last surge yielding a "tidal wave" seems to have ended the settlement with a maximum depth of around 22 feet (6.7 m) estimated from observation of a power pole in the cenre of the area."

"Activity seemed to cease at this time, and no further settlement has been observed at the time of writing(September 3, 1954). Minor adjustments of the soil were noted, but were not attributed to subsidence, but rather to adjustments of clays in the subsoil due to very heavy rains the week preceding and the release of restraining pressure on the soils in the direction of the sink."

"A preliminary profile survey of the water-covered area was made by taking soundings along cross-section lines...The water-filled depression was found to contain a circular sink on the west side, symmetrical with the east-west axis; the maximum depth noted was 22.7 feet".

"A definite scarp was found to exist along the west side of the sink and along sloping shelf is reported on the north, south, and east".

"Cracks and fissures ranging up to a foot in width and 100 feet in length were observed in the soil and roadways concentric with the sink hole on a spacing of about ten feet, extending perhaps 100 feet from the edge of the water which had filled the sink virtually to river level. Cracks in the soil passed on both sides of the gas holders, indicating their precarious position".

"The chlorine liquefaction buildings were practically under water; the pumphouse was inundated to the second story. It is interesting to note that the pumphouse moved essentially straight downward - the component of tilt being far less than that of settlement."

"Cracks due to tension resulting from differential settlements were noted in the walls of almost all of the buildings of the two plants, and in some cases mortar was broken along the same lines it had been repaired previously...Courses of bricks were seen to curve downward in the direction of subsidence, and a railroad track oriented tangentially to the sink was visibly deformed in the direction of the settlement. These observations substantiate the belief that as the subsidence developed, movements, both vertical and horizontal, took place".

"The sink hole was pumped dry in the following months...In refilling the sink, 70,000 cubic yards (53,520 m^3) of sand and gravel were used to fill the 75% of the area which lay within Canadian Salt Company boundaries. It is estimated that an additional 15 - 20,000 cubic yards (11.5 to 15.3 thousand m^3) will be required to fill that portion on CIL property, although at present it is intended to keep this area open to dispose of the debris of demolition of the CIL buildings."

"Dewatering operations were readily accomplished, as most of the water in the depression apparently was derived from the torrential rains preceding the event and from broken pipelines at the time of sinking. Further settlements in the area have been negligible and all are attributed to adjustments in the underlying clays in the area of the hole, due to release of pressure in that direction".

TERZAGHI (1970, p. 302) places particular emphasis on "a rapid subsidence, amounting to approximately three feet, around one side of the rim of the depression at about 1:45 p.m."; according to a photograph (LANDES and PIPER, 1972, p. 40), the fissure along the western rim of the so-called sinkhole, where the "rapid subsidence" took place, runs approximately straight in the north-south direction, tapering out when approaching the southern edge.

This means that at least the "original edge of sinkhole" at the south-west corner is better represented by a right angle than by a smooth curve, see Fig. 6-10. TERZAGHI (1970, p. 303) describes the so-called sinkhole as "roughly elliptical in shape, with a maximum diameter of nearly 500 feet and a maximum depth in excess of 25 feet. The pond occupied the centre of a larger bowl-shaped depression with a radius of about 1000 feet". Her "successive profiles", Fig. 6-11, cannot be reconciled with her quoted statements.

It is specifically emphasized here that "the maximum depth noted was 22.7 feet" but not far in excess of 25 feet as shown in Fig. 6-11.

6.3.7 Investigations after "sinkhole" formation

According to TERZAGHI (1970), "subsequent investigations indicated that sudden important subsidence was the culminating event in a progressive failure of strata overlying a solution cavity produced by brine extraction from salt deposits located at depths in excess of 1000 feet below the surface of the ground."

The following points are stressed with reference to the subsidence characteristics shown in Fig. 7-1. In the first place, the radius of the general subsidence trough along AB, Fig. 6-8, measured over 800 feet. The depth to the original roof of cavities dissolved in salt was approximately 950 feet, see Fig. 6-13. Unless large supporting remnants of salt existed in the brine field, considerable surface subsidence had to be expected.

Secondly, three boreholes were drilled into the localized subsidence trough, the so-called sinkhole, after the rapid subsidence in

1954. These three holes, shown on Fig. 6-14, encountered bedrock (limestone) in place underneath the unconsolidated near-surface sediments.

This writer considers Fig. 6-14 as undisputable proof of the fact that there was not a circular chimney extending down to a cavity in salt, as postulated by various writers (LANDES and PIPER, 1972; JEREMIC, 1975; NIETO-PESCETTO and HENDRON, 1977, with reference to an unpublished report (PECK, 1954); other writers, see 6.5).

The brining operations in the Sandwich field were terminated in 1954; the so-called sinkhole was filled with sand and gravel.

According to TERZAGHI (1970, p. 305), "the apparently constant rate of settlement of about one inch per year presently experienced by three of the reference points in or near the sinkhole area is of the same order as observed in many areas where salt extraction has been practiced".

The postulated surface crater, the sinkhole, did not re-appear after being filled with sand and gravel. This is a sharp contrast to previously reported case histories of surface cratering due to salt extraction; in all known cases of surface cratering under comparable conditions, the craters re-appeared after being filled. In some well-documented cases the craters developed into rather deep lakes, see 3.2.

TERZAGHI's (1970) report on the post-subsidence investigation reads as follows.

"Following the formation of the sinkhole, the Canadian Salt Co. and Canadian Industries Ltd. retained a panel of consultants; the program recommended by the panel included the determination of the depth to bedrock in the sinkhole area by means of a large number of washborings. Before any borings had been made, a seismic survey was carried out at the suggestion of BAYS. After a contour map of the bedrock surface had been prepared on the basis of that survey, three holes were drilled to bedrock; one of these was near the deepest part of the sinkhole, one on the westerly slope of the depression, and the third, in line with the other two, was slightly east of the westerly shore of the pond occupying the sinkhole area."

"The results of the drilling indicated that the seismic survey

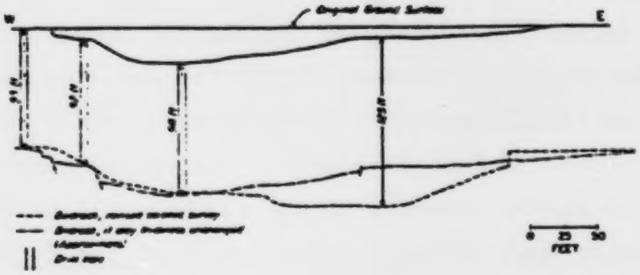


Figure 6-14: East-West section through sinkhole (from TERZAGHI, 1970, Fig. 8).

had overestimated the depth to bedrock by sixty to eighty feet within that part of the sinkhole area where the measured depth was 92 to 98 feet. After the results of the borings became available, the results of the seismic survey were recomputed."

"Figure 6-14, an east-west cross section through the sinkhole, shows the results of soundings in the sinkhole pool, the depth to bedrock determined at three points by borings, and the revised results of the seismic survey. According to the seismic survey, the Pleistocene deposits were as much as 25 feet thicker beneath the easterly part of the depression than beneath the westerly part, where the observed thickness of 92 to 98 feet is close to the values recorded in the logs of brine wells in the vicinity of the sinkhole (95 to 94 feet). In the absence of additional borings, the accuracy of the recomputed results of the seismic survey cannot be regarded as established." (underlined by this writer).

"Within the period of four months following the formation of the sinkhole, two sets of settlement observations were carried out. Both of these surveys included reference points in the area located to the northwest of the sinkhole, as well as those in the southwesterly section which had not been surveyed since 1950. The results of the levelling showed that rather irregular movements of small magnitude had taken place within this period."

"Some points went up whereas others settled. In general, additional settlements of as much as one inch had taken place in the zone adjacent to the sinkhole pond; settlements of other parts of the brine field were within the limits of error of the survey."

"Because of a change of ownership, observation of reference points in the northwesterly part of the subsiding area was discontinued after 1954. In the southwesterly quadrant, however, the Canadian Salt Co. carried out annual surveys of some thirty reference points, about half of which had been in existence since 1948 (Fig. 6-15). Most of the points under observation have settled at average rates of less than one-fourth inch per year since 1954, and the settlement of many of them appears to have ceased altogether."

"The settlement of points located at a distance of 200 to 500 feet

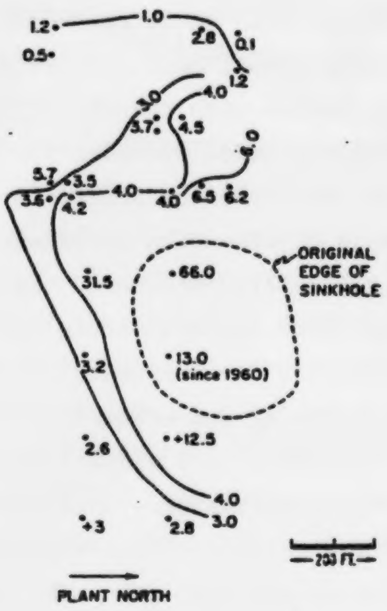


Figure 6-15: Subsidence in inches, 1954 to 1968 (from TERZAGHI, 1970, Fig. 9).

from the sinkhole area is scarcely perceptible. Their average annual rate of settlement over the 14-year period following sinkhole formation does not exceed about one-seventh of the average annual rate observed from 1948 to 1950 (the only years for which data are available for this part of the subsiding area), and it therefore appears that the formation of the sinkhole coincided with the end of the process of widespread, accelerating subsidence which preceded it."

"Only four of the reference points in the southwesterly area have experienced a change of elevation in excess of 6.5 inches in the period of observation (1954-1968). Of these, two are located within the sinkhole area, and the other two are within 100 feet of it."

"The data suggest a northwestward or westward tilt involving a subsidence of 66 inches at the westerly end of the tilted area, and an elevation of 12.5 inches of the easterly end. The tilting movement took place at a rapidly decreasing rate until about 1965, when the rate of movement of the three subsiding points seems to have assumed a fairly constant rate of about one inch per year. The reference point which went up had apparently become stationary by the beginning of 1967."

This writer considers the contouring near the point with 31.5 inches of vertical displacement as incorrect; there is no justification for connecting the 4-in.-contour line through this area as shown on Fig. 6-15.

The two points with the highest measured vertical displacement of 66.0 and 31.5 inches are lined-up exactly in the north-south direction, i.e., parallel to the western edge of the so-called sinkhole which also runs nearly straight north-south as emphasized at the end of 6.3.6. The presence of karst cavities extending north-south along the western edge of the so-called sinkhole appears strongly indicated.

TERZAGHI (1970, p. 305) continues her assessment of post-subsidence investigations as follows: "Inasmuch as the notable subsidence in the years following sinkhole formation took place at a rapidly decreasing rate, it is probably attributable to settlement and re-adjustments in the rock debris underlying the broken rock surface at depth. The apparently constant rate of settlement of about one inch per year presently experienced by three of the reference points in or near the sinkhole area is of the same order as that observed in many areas where salt extraction has been practiced. It appears to result from the slow creep of salt pillars, whether left by design in salt mining or fortuitously during brine extraction. It differs qualitatively as well as quantitatively from the accelerating subsidence associated with progressive roof failure."

The presence of salt pillars underneath the area of rapid localized subsidence appears most unlikely to this writer in view of the morning-glory shape of the individual cavities which became eventually connected to a "general" cavity. To explain the rapid subsidence associated with the formation of the so-called sinkhole, it would be necessary to assume the failure of salt pillars which were left fortuitously in the centre of the bowl of general subsidence.

As a matter of fact, exactly that is postulated by JEREMIC (1975), see 6.5. Needless to say that failed salt pillars cannot control overburden subsidence to the effect that the surface subsidence terminates for all practical considerations.

However, "settlement and re-adjustments in the rock debris" in the "general cavity" appears to be an acceptable interpretation of surface subsidence "at a rapidly decreasing rate". Eventually, after all available space underground has disappeared due to displacement of mobile sediments, the surface subsidence in the central area of the brinefield will cease as it virtually ceased at some distances from the so-called sinkhole.

6.3.8 Mechanism of subsidence

TERZAGHI (1970, pp. 305-307) offers "two alternative hypothetical models of the events which led to the sinkhole formation".

"After the formation of the sinkhole...it was clear that the gradual subsidence of an area with a diameter of about 2000 feet as well as the rapid subsidence of its central portion were the result of the collapse of the roof of one or more cavities in underlying salt beds. Nevertheless, the data then available left a number of unanswered questions".

Referring to an unpublished report the writer outlines the alternative hypothetical models as follows:

"One involved subsidence of only that part of the rock surface which underlies the sinkhole, i.e., localized rock subsidence. The second involved the more conventional hypothesis of the subsidence of the rock surface underlying the entire subsiding area, i.e., general subsidence".

Apparently, the term "rock surface" refers to the bedrock surface. The first hypothesis is that of chimneying dealt with in more detail in 6.5. The second hypothesis is dealt with in Chapter 7.

"Concerning the hypothesis of localized subsidence," the writer quotes from her reference report as follows: "If the bedrock surface surrounding the sinkhole area remained practically stationary throughout the years, the observed subsidence can only be explained by assuming that the bedrock surface in the sinkhole area...descended through a space with a volume equal to that through which the surrounding ground surface moved down. It must further be assumed that the clay advanced in radial directions towards the sinkhole area, from distances of more than one thousand feet..."

"...Yet a flow of clay over such distances...beneath an almost horizontal surface is a process without known precedent. Therefore the writer cannot accept it unless check borings show that the quantity of clay located above the subsided portion of the rock surface has really increased..."

According to TERZAGHI (1970, p. 305) "the recommended check borings were never made." However, Fig. 6-14 shows 3 boreholes which revealed bedrock in place underneath the so-called sinkhole. Apparently, the reference paper was written before the holes were drilled.

The thickness of unconsolidated near-surface sediments was found unchanged, see 6.3.1. "It thus appears that the hypothesis of localized subsidence (chimneying) is no longer tenable."

"If, as suggested by the second hypothesis, the subsidence of the ground surface was everywhere essentially identical with that of the bedrock, the rock surface underlying a large area outside of the sinkhole subsided at rates which were locally as great as 7 inches per year. Such a rate of subsidence could be explained only if this area were underlain by one or more cavities with inadequate roof support."

With reference to Fig. 6-11, the writer emphasizes that "the profiles exhibit a form similar to that of a loaded, clamped plate of which the clamped edge is subsiding at a rate of about one-half inch per year. The postulated plate consisted of rock strata with an initial thickness of at least 900 feet."

"The initial deformation of such a plate would be very small but a progressive decrease of its thickness associated with the dropping of strata or packets of strata into the underlying cavity would lead to increasing deformation of the plate and hence increasing settlement of points on the surface of the ground."

At this point, the different mechanical properties of the various overburden formations and particularly the significance of karst features are re-emphasized. With particular reference to Chapter 7, the reader is reminded of the well-established characteristics of surface subsidence troughs. However, the comparison of the overburden of the Sandwich brinefield with a clamped plate has some merits with regard to cavities of limited span.

"on the hypothesis that subsidence was the surface expression of the deformation of a roughly circular clamped plate, the episode of rapid and catastrophic subsidence of February, 1954, can be interpreted as the result of the failure of the remaining strata which could no longer carry their own weight plus that of the overlying unconsolidated deposit."

This interpretation appears acceptable. However, the significance of linear karst features and faults intersecting the entire overburden must not be ignored as emphasized repeatedly.

Compared to other cases of rapid subsidence, see Chapter 2, the Windsor events should not be called "catastrophic." They certainly were costly because the plant installations were damaged and the brinefield had to be abandoned.

TERZAGHI (l.c., p. 306) admits that "it is not possible to determine accurately the diameter of the area undergoing accelerated subsidence, corresponding to the diameter of the postulated clamped plate, because settlement observations were not made throughout the entire bowl of subsidence. However, available data provide a basis for an estimate of maximum and minimum values."

Referring to Fig. 6-11, the writer claims that "the clamped edge of the postulated plate was descending at an approximately constant rate, whereas the remainder of the plate was undergoing deformation at a generally increasing rate. Hence on the map shown in Fig. 6-12 (reproduced from PECK's 1954 report), the location of the clamped edge can be assumed to coincide approximately with the contour representing zero difference between the 1949 rate of subsidence and the 1953 rate. The distance from this contour to the point of maximum subsidence before sinkhole formation is approximately the radius of the clamped plate subject to deformation."

"If this point was located near the centre of the sinkhole area, the radius was approximately 750 feet. However, the centre of subsidence preceding failure was not necessarily identical with the centre of the sinkhole, because the location of the sinkhole was probably determined by the location of that part of the cavity with maximum original vertical dimension, which was not necessarily at the centre of the subsiding plate. As a matter of fact, settlement observations made in 1950 suggest that maximum settlement in 1950 occurred in an area several hundred feet to the southwest of the centre of the sinkhole. If this area was the site of maximum subsidence throughout the years 1951 through 1953, the effective diameter of the clamped plate may have not exceeded 650 feet."

The apparent shift of the maximum subsidence rates toward the centre of the subsiding area is re-emphasized. As a matter of fact, the subsidence rate in the area of the future sinkhole decreased, as would be expected if indeed the diameter (span) of that area was smaller than the overburden thickness. Cavities in the sinkhole area may have been filled with broken roof strata up to the "clamped plate".

In addition, the plate with reduced thickness was supported by water pressure, and possibly by remnant pillars of salt. Apparently, Detroit river water entered through linear karst features to recharge the aquifer which consisted of salt cavities and permeable overburden.

There are apparent similarities with the situation dealt with in 6.2.

This writer cannot agree with the assumption that "the location of the sinkhole was probably determined by the location of that part of the (general) cavity with maximum original vertical dimension." The horizontal dimension, i.e., the span of the cavity, and the location of linear karst features are more significant.

"Although it is impossible to determine with precision the time at which the thickness of the cavity roof began to decrease, the records of well abandonment provide some general information. Of the nine wells drilled within the area of the bowl of subsidence or at its periphery, all but two had been abandoned by 1932 owing to severe damage produced by rockfalls. Two survived into the 1940's. One of these, located about 500 feet southeastward of the centre of the sinkhole, was abandoned in 1940 owing to a rockfall at a depth of 965 feet."

"The second, located about 100 feet east of the first, was abandoned in 1943 because of irreparable damage at a depth of 1200 feet. Hence it seems that the strata at depths less than 1000 to 1200 feet were still fairly intact in the early 1940's beneath the site of the future bowl of subsidence; otherwise rockfalls would have taken place in the remaining wells at higher elevations. By 1950, when the bowl of subsidence first became perceptable, progressive failure must have reached a level well above the Upper Salt."

It is re-emphasized that the surface subsidence contour lines from 1948 to 1953 clearly indicate the W-E direction of the flow of recharge water to production wells.

The apparent shift of maximum subsidence rates in the same direction is also re-emphasized.

The quoted statements require the following remarks.

(1) The bowl of general subsidence "first became perceptable by 1950" only because the subsidence measurements commenced in October 1948. At that time, damage to plant buildings made it obvious that surface displacements, including vertical settlement, were already in progress, see 6.3.1.

(2) The thickness of failing roof strata depends on the span of any individual cavity. Roof failure at higher elevations indeed would have taken place at the site of the two

reference wells if a "general cavity" had already developed in the early 1940's.

(3) It is stressed that the two wells which survived into the 1940's were located east of the so-called sinkhole; the reason why these two wells survived appears to be the apparent west-east flow of recharge water from the Detroit river.

(4) The shift of high rates of surface subsidence from an area west of the so-called sinkhole towards the centre of the bowl of general subsidence is re-emphasized.

For these reasons the observations on the two reference wells must not be considered indicative of a "fairly intact" overburden plate with the calculated thickness.

"Subsidence like that at Sandwich is commonly attributed to stoping above a large cavity located at depth, followed by collapse of the remainder of the roof of the cavity. However, if it were assumed that the Sandwich subsidence was due to the presence of a single high cavity, into which much of the roof rock, with a total thickness in excess of 1000 feet, had dropped, it would be virtually impossible to account for the fact that bulking of the debris had not caused the cavity to be filled before major subsidence could take place."

"An alternative hypothesis is that early cavities were extensive and locally deep, but contained abundant salt pillars which provided temporary and partial support for a sagging roof. According to this hypothesis, if strata overlying a cavity became separated along bedding planes from the rocks above and sagged into the cavity, they did not descend far before coming to rest at least temporarily on salt remnants. When the next set of strata in turn became detached from the overlying rock, they also came to rest in a nearly intact state and only slightly below their original position. These strata must have been thoroughly fractured and entirely lacking in tensile strength, but the space which they occupied need not have been greatly in excess of their original volume. It can, for instance, be postulated that the 150-to 200-foot stratum of insoluble rock between the Lower and the Middle Salts sagged into one or more underlying cavities. More or less simultaniously, it may be supposed, similar sagging took place into the cavity or cavities in the Middle Salt."

It appears difficult to visualize that "thoroughly fractured" strata separate along bedding planes, sag into a cavity, and come to rest "in a nearly intact state" without considerable bulking. Bulking means considerable increase in volume. Observations in conventional mines definitely contradict such hypotheses. However, if the fractures are filled with salt, which is commonly the case, the dissolution of the fracture salt would result in some decrease in rock volume and offset some bulking effects. Needless to say that such roof rock desintegrates to become a so-called breccia upon recompaction; it definitely does not "come to rest in a nearly intact state".

TERZAGHI (1970, p. 307) postulates that the dolomite strata "overlying the Upper Salt were initially thick enough to span a cavity in the Upper Salt without appreciable deformation. Eventually, however, partings along bedding planes must have opened, whereupon one or more strata descended into the cavity, possibly without disruption or notable bulking. As successive strata were detached from the roof and came to lie on the floor of the cavity, the load on the salt remnants at various deeper levels was increased and must have produced failure of some of the salt pinnacles which provided support for the overlying broken strata."

"Concurrently, solution was taking place in the salt beds, owing to the fact that water was being introduced through well No. 19, west of the subsiding area, while brine was being pumped from wells located east of it".

Well No. 19 is located in the area of zero change in rates of subsidence, see Fig. 6-12; east of it, the total subsidence from October 1948 to October 1953 amounted to 5 inches (12.7 cm) and less according to Fig. 6-11. Apparently, most of the recharge water was not flowing east from well No. 19, but from an area south of that well where up to 7 inches (17.8 cm) of subsidence took place from October 1952 to October 1953; the total subsidence from 1948 to 1953 amounted to more than 12 inches (30.5 cm) west of the "original edge of sinkhole". As outlined in 6.3.3, these established facts are considered indicative of hidden linear karst features in non-salt evaporites, including the roof dolomite of the Upper Salt.

For this reason, and because of the above-mentioned probability of salt dissolution out of fractures in the roof dolomite, the hypothesis of roof strata "initially thick enough to span a cavity in the Upper Salt without appreciable deformation" cannot be accepted. Also inacceptable is the hypothesis that roof strata separated and sagged to the floor "without disruption or notable bulking". If successive strata separate from the roof and come to lie on the floor, the load on "salt pinnacles" at deeper levels is definitely not increased when the salt cavities are washed out above each other; to the contrary, each piece of rock that falls to the floor diminishes the load transferred by bridging roof formations. For this reason, the following assumptions (l.c., p. 307) are inconclusive:

"Both the increasing load on salt remnants and their continued diminution by solution must have contributed to a gradual increase in the settlement of the overlying broken strata resting on them, and henc to an increase in the height of the cavity spanned by intact rock. There seems to be no way of determining the stage at which the vertical dimension of this cavity became so great that there was notable shattering and bulking of the strata as they dropped into it".

There is no question as to the increase of loads on remnant pillars when the size of the remnants is continually decreasing; however, in cases where broken roof strata fall to the floor of a cavity, the broken rock is not resting on remnants. The decreasing size of the salt remnants causes the increasing loads as long as overburden formations continue bridging the cavity.

Highly increased loads on "salt pinnacles" may cause creep deformation at relatively shallow depths, and corresponding subsidence of the overburden as shown in Chapter 7.

Regarding the vertical dimension of the cavity underneath the so-called sinkhole at Windsor, TERZAGHI (1970. p. 307) is quoted as follows: "It is only known that when the roof finally failed, the vertical dimension of the cavity exceeded that of the broken rock by twenty-five feet in the deepest part (of the so-called sinkhole), and by only a few inches at a distance of several hundred feet from the centre.

The remainder of the cavity was completely filled with broken rock, either at the time of sinkhole formation or in the few months prior thereto. Consequently little or no sudden subsidence took place in the area located more than some two hundred feet beyond the edge of the sinkhole area".

These statements need the following comments:

(1) The writer fails to consider lateral displacements. Therefore, measured vertical surface subsidence must not be identified with the vertical dimension of an underlying cavity.

(2) It is not known which member of the overburden finally failed in a manner similar to that observed on occasion of rockbursts in German potash mines, see Chapter 2. Agreement appears to exist regarding failure in tension of the respective overburden formation. The fact that there was no violent failure at Windsor is considered as indication of existing vertical fractures and/or linear karst features in two preferred directions. There is no way of predicting the time at which overburden subsidence results in tension sufficient to eliminate the plate-like behavior of a bridging formation.

(3) The apparent shift of maximum subsidence rates towards the so-called sinkhole is re-emphasized. In view of the unlimited recharge of the brinefield from the Detroit river, this writer considers the overburden support provided at all times by water/brine in the cavities as an important factor. Lateral displacement of deteriorating debris and/or of mobile near-surface sediments may have taken place. Therefore, the so-called sinkhole cannot be considered as evidence of open space underneath its location.

As the writer puts it with reference to Fig. 6-14 which suggests an increase of as much as 25 feet (7.6 m) of the Pleistocene deposits beneath the easterly part of the so-called sinkhole: "In the absence of additional borings, the accuracy" of the suggested increase "cannot be regarded as established."

6.4 SURFACE CRATERS IN BRINEFIELDS

6.4.1 Studies sponsored by the Solution Mining Research Institute

The Solution Mining Research Institute (SMRI) initiated several studies of the mechanism of overburden subsidence in brinefields as outlined in 6.3.4. Some published studies are to be discussed in the following.

This writer disagrees particularly with the postulated formation of small-diameter chimneys from cavities in salt up to the surface.

NIETO-PESCETTO and HENDRON (1977, forword and preface by PIPER) are introduced as principal reviewer of field data and as "principal advisor, for many years,...on Rock Mechanics, the technology upon which this study is based".

"The Institute's study of surface cratering visualizes a four part program: explanation of the mechanism, its mechanics, causes and time frame; techniques for detection of subsidences with potential for surface cratering; exploration into methods for arrest of the activity; and ultimately development of technology of salt well operation directed to prevention of surface cratering".

In his preface, PIPER (1977) explains: "Sinkhole is the term employed by the semi-scientific community to refer to a breach or collapse of the earth's surface resulting from causes largely unknown but generally agreed to be localized in the subsurface directly beneath. The term has dire inferences because it is not specific in cause, time frame or areal extent. The uninformed expects the worst".

"Use of the term to describe surface collapse resulting from removal of salt and the upward migration of the cavity through the overlying rock layers to ultimate intersection with the earth's surface (actual cratering occurs at this time) is unfortunate because the mechanism is accurately visualized and the area of influence recognized to be relatively localized thus precluding engulfment of an expanding area. The term is deserved in that adequate effort has not been made by salt producers to develop an explanation of the mechanism - a prime requisite to laying the matter to rest".

"This report is directed to such an investigation. Two areas of brine production in the Detroit area produced surface craters in modern times, each documented by engineering data on salt production (well histories) and surface deformation (elevation surveys) which lend themselves to review and development of an explanation of the mechanism. This in turn contributes to development of aspects of limits of extraction and further in due course to constraints which lead to prevention".

"Salt of Salina age has been produced in the area of Detroit, Michigan, by solution mining methods dating to 1890. The salt was used in salt manufacture and as a raw material for chemicals. Many plants were sited in this area and many tons of salt were produced each year from brine fields which went largely unnoticed in this supply function but which ultimately developed cavities which had the required geometry to involve the surface. This report is a study of the data available on two localities that did - and by comparison one that didn't - all developed in recent times and offering data adequate for analysis. All have been replaced by installations laid out in a manner to preclude damaging surface settlements".

One area is dealt with in 6.3. "A second area considered in this report is the Grosse Ile brine field of BASF Wyandotte Corporation... actually part of an island in the Detroit River, operated to support chlorine and soda ash plants located in the city of Wyandotte nearby. Surface cratering - actually two separate craters concurrently - occurred in the Grosse Ile brine field in 1970. Operations were terminated and a new production system installed".

"Also to be considered is the brine field operated by the Wyandotte company at the site of one of its Wyandotte plants - referred to as the Wyandotte North Works. Appreciable salt was produced. Production was terminated in 1950".

"Since it is best documented in terms of well histories, production records, geological tests and surface elevation measurements, this report will consider Grosse Ile primarily with reference to the subsidence at Windsor and lack of settlement at the Wyandotte North Works by comparison".

As emphasized in 6.3.4, this writer disagrees with the "accurately visualized" mechanism of chimneying. For this reason a detailed discussion of the reference report (NIETO-PESCETTO and HENDRON, 1977) on the Grosse Ile craters is presented.

6.4.2 Sinkholes on Grosse Ile

6.4.2.1 Objectives of study

NIETO-PESCETTO and HENDRON (1977, p. 4) consider as the primary objective of their study "to present an analysis of the possible causes and mechanisms which resulted in sinkhole formation at Grosse Ile based on a review of measured surface settlements, production records, and brine well drilling and maintenance records".

"The Grosse Ile brine field is located near Wyandotte, a suburb of Detroit, Michigan, on the northern tip of Grosse Ile, an island in the Detroit River. The northern tip of Grosse Ile is called Hennepin point which is the actual site of brine operations...commencing in 1943 and continued until two sinkholes formed in the late part of 1970 and early part of 1971. A detailed description of events and witness reports of the final stages of development of these sinkholes is given by LANDES and PIPER (1972)".

"The development of the Grosse Ile sinkholes raised questions about the state of the art in predicting the point at which brining operations should be stopped or modified in order to prevent the formation of sinkholes. Thus, another objective of this study was to define guidelines which could be used to indicate sufficiently in advance when a potentially dangerous situation is imminent so that operations could be ceased or appropriately altered".

"Since surveys of surface subsidence are or could be conducted at all brine fields where the operators are seriously attempting to control subsidence, it seemed reasonable that these guidelines should be developed in terms of the observed pattern of surface settlements in order to be useful for engineering application."

"The Grosse Ile brine field case history offers a unique opportunity from this point of view because surface settlements were surveyed for 18 years preceding the development of the sinkholes. Thus the Grosse Ile brine field represents one of the most thoroughly documented brine fields where sinkholes have actually occurred".

"Because the geologic conditions at Grosse Ile are nearly identical to the geologic conditions at the Wyandotte North Works and the Canadian Industries Windsor brine field, comparisons have been made between the behavior observed at these brine fields and that observed at Grosse Ile. The comparisons are significant because a sinkhole also developed at the Canadian Industries Windsor brine field in 1954 (TERZAGHI, 1970) and because brining operations were stopped at the Wyandotte North Works before a sinkhole formed, even though the average volume of salt removal per unit area of brine field at the Wyandotte North Works was nearly the same as the Grosse Ile brine field."

"The comparative study of the performance of these neighboring brine fields has resulted in "guidelines" which can be utilized with the observational approach in order to engineer brining operations without the attendant formation of sinkholes".

As stated at the beginning of the quotations, this writer cannot agree with the postulated formation of small-diameter chimneys from cavities in salt up to the surface. The Grosse Ile sinkholes are given primary consideration as "best documented in terms of well histories, production records, geological tests and surface elevation measurements". However, the guidelines developed to engineer brining operations without the attendant formation of sinkholes need careful scrutiny, particularly in view of the fact that the writers apparently consider their guidelines valid under any geological conditions in bedded salt deposits.

The writers (1977, p. 6) present the following "statement of problem and scope": "It has been long known that solution mining of bedded deposits may bring about two modes of surface subsidence at an active brining field. The first type, henceforth referred to as downwarping or generalized subsidence, affects a relatively large area, has very gentle surface gradients and results in recognizable but small surface settlements confined to the area of the brine wells. Areas of limited extent within the area of solution mining, usually from a few hundred to about 1500 feet in diameter, sometimes settle considerably faster than the surrounding area and develop greater surface gradients. This latter type of settlement is defined here as localized subsidence".

These statements ignore the significance of the geological conditions of any specific brinefield and are unacceptable; it is absolutely necessary to take the subsidence characteristics under specific geologic conditions into appropriate consideration, as shown in Chapter 7.

The writers continue their statements as follows:

"In all the documented cases of sinkhole formation in the Michigan Basin, the sinkholes have occurred within zones of localized subsidence. These areas of localized subsidence, with or without attendant sinkhole formation, are often cited as the reason for the early termination of brining in fields which were developed under critical surface installations. Although the problem of potential damage to structures has practically been eliminated by developing brine fields away from sensitive areas, recent environmental concerns and the publicity which accompanies the formation of a sinkhole have detrimental effects on public acceptance of brine field operations, calling for conservative design criteria".

"In addition, there is considerable interest in using brine field cavities for gas storage. Before gas storage in these cavities is generally accepted it will be necessary that the technical community gain a better understanding of the mechanism of sinkhole formation and be able to decisively state that a given brine field can be considered to be safe for this application".

"This paper is part of an effort to elucidate the mechanis of subsidence and sinkhole formation in brine fields developed in flat lying rocks by means of studying the documented behavior of brine fields where sinkholes have (Windsor, Grosse Ile) and have not (North Works) occurred. A large part of this paper is a review and an interpretation of the brining operations and observed behavior of the Grosse Ile brine field. The general geology and geologic details of the Detroit area will be discussed. Production and development of Grosse Ile brine field will be reviewed, as will appropriate records of surface subsidence at Grosse Ile. Comparisons will also be made with subsidence records from the Canadian Industries Windsor brine field and the

Wyandotte North Works. An interpretation of the settlement patterns observed at Grosse Ile is also given as it relates to the geologic details of the site and the development of the brine field".

These statements need discussion and corrections presented as follows.

6.4.2.2 History and geology of the Grosse Ile brinefield

LANDES and PIPER (1972) give the following summary: "The northern end of Grosse Ile, Point Hennepin, is owned by...BASF Wyandotte Corporation, and was originally purchased as a place to pond wastes from the chemical plants on the mainland to the west. The fine-grained light-colored tailings are delivered in slurry form by pipeline to the island where they are ponded and drained. The maximum thickness is 30 feet; beneath is a few feet of organic soil at or below river level".

"Most of Grosse Ile is a glacial moraine consisting of about 60 feet of clay with scattered boulders. Between the top of the bedrock and the top of the salt measures is 500 feet of nearly flat stratified rock consisting in descending order of impure dolomite, sandstone, and more impure dolomite. The rock section that contains the salt is about 730 feet in thickness; the more massive salt beds are toward the base, at depths between 1100 and 1300 feet", see Fig. 4-3.

The writers elaborate as follows on the "man-made overburden" on Grosse Ile near Point Hennepin: "This is a plateau consisting of the solids resulting from ponding of plant wastes...It is white and exceptionally fine, mostly less than 44 microns in diameter. Where freshly exposed on the walls of the collapsed craters, this synthetic sediment is strikingly stratified, resembling a lake clay deposit. Chemically, the principal constituents are calcium carbonate, calcium sulfate, and calcium hydroxide, plus silica and other insoluble impurities which were in the original limestone material used in the chemical operation that produced the waste."

"The waste sediment was transported to the ponding area in a liquor of calcium and sodium chlorides; and films of residual liquor containing these dissolved salts remain with the microscopic particles. Because of the extreme fineness of grain this man-made overburden is practically impermeable, preventing the washing out of the chloride liquor".

"The material accumulated to a height of approximately 30 feet above river level before the disposal was terminated in 1948-50. Brine production started to a limited extent in 1941 at Point Hennepin around the perimeter of the island concurrent with the ponding operation. Prior to this time brine was produced from wells located within the plants themselves on the mainland. Upon termination of tailings disposal and the adequate drying and solidification of waste material, access roads were built and wells were drilled over the rest of Point Hennepin".

"Below the tailings is about 60 feet of glacial drift beneath a thin veneer of organic marsh soil. The dirft is part of the Grosse Ile moraine...There is no record of any continuous stratified sand or gravel within the glacial drift; the dirft layer serves as a seal for vertical migration of ground water".

The man-made overburden on Grosse Ile differs significantly from the natural overburden of the Sandwich brinefield and of the Wyandotte North Works.

For unknown reasons NIETO-PESCETTO and HENDRON (1977) fail to mention the relavant difference of the man-made overburden on Grosse Ile where near-vertical sinkholes could develop and persist for some time.

In contrast, the so-called sinkhole at Windsor and the "localized subsidence "trough at the Wyandotte North Works developed surface gradients because of the apparent weakness of the unconsolidated near-surface sediments.

The photographs included in the reports by PIPER (1954), TERZAGHI (1970), and LANDES and PIPER (1972) demonstrate the difference in the behavior of natural near-surface sediments and of the man-made sediments at Grosse Ile.

However, the photographs of the Grosse Ile sinkholes in the latter publication also show that the "vertical cliffs" soon started crumbling into the holes due to the removal of lateral constraint.

A review of the further development of this process most certainly would have aided NIETO-PESCETTO and HENDRON (1977) in acheving the objectives of their investigation which pretends that nothing happened since 1971.

6.4.2.3 History of brining operations on Grosse Ile

NIETO-PESCETTO and HENDRON (1977) claim to present a detailed production history for each of the 72 wells and one experimental well drilled in the Grosse Ile brinefield. However, records for the first 6 wells are missing, possibly because the wells were drilled before 1943 and are located south of what is called the Central Gallery.

Records are also missing for the following wells:

(1) No. 10, operated as a single well throughout its lifetime according to LANDES and PIPER (1972, p. 20).

(2) No. 11 and No. 33 which developed into a "minor gallery" according to the same writers.

(3) No. 40, located in the Central Gallery, but operated as single well for an unknown period of time.

(4) No. 61 through No. 66, Nos. 70, 73, 75, 76, and 78, all located south of the Central Gallery. Apparently, it is assumed that none of these wells was ever connected to the Central Gallery.

"In assigning production to a given well location it was assumed that dissolving of salt in the area of a well was proportional to the quantity of fresh water injected in that particular well when it was used as water inlet well". The summary of yearly production ascribed to each well "shows that the North gallery was the primary source of salt before 1960 and the Central gallery was the more heavily utilized gallery after 1960. The total production of all wells in the North and Central galleries was about 412 million cubic feet of salt".

"This corresponds to an extraction ratio of about 50 ft^3 of salt per ft^2 of solution mining area. The solution mining areas was assumed to extend approximately 200 ft outward from the peripheral wells in both galleries".

Extraction ratios are usually given as percentages of extracted mineral in relation to available mineral of a given mineral bed. According to the writers "the principal salt bed at this location is the 200 ft. thick Salina Unit B (salt No. 4); the extraction of approximately one fourth of the total thickness gives an extraction ratio of 25%. Taking into account that "interbeds of dolomite, anhydrite, and salt-impreganted, shaly dolomite...constitute 20% of the gross thickness", one arrives at the extraction ratio of 40%.

According to a "typical core log of Hennepin Point brine field" (LANDES and PIPER, 1972), the depth to the top of the Salina B Unit (salt No. 4) is approximately 1100 feet. The maximum span of the North gallery is approximately 1200 feet between wells, and 1600 feet if the assumed outward extension from the peripheral wells indeed took place.

For the Central gallery, the corresponding dimensions calculate as follows: maximum span between wells 1600 feet; maximum span of gallery 2000 feet."

As NIETO-PRESCETTO and HENDRON (1977) compare the Grosse Ile galleries with the Sandwich brinefield at Windsor, the corresponding dimensions are listed as follows: depth to the top dissolved salt bed approximately 1000 feet; maximum span (assumed diameter of subsidence bowl) 2000 feet.

The dimensions of the Central gallery and the Sandwich subsidence trough compare well. However, the considerably smaller span of the North gallery should be noted. The writers fail to give any dimensions for the Wyandotte North Works brinefield.

The writers include "an experimental well designated as X-2" in their production history. Apparently, one of the "four exploratory holes, X-1 through X-4, drilled in 1969" in the central area of the Central gallery was used as production well. However, the production record of well X-2 commences in 1967, while X-1 was completed in 1966. This writer was unable to clarify the apparent contradiction.

The four exploratory holes failed "to show any evidence of appreciable open cavities within the Unit B or in the overlying rock section. Although the base of the B salt was found intact, it is difficult to determine if these boreholes penetrated the entire salt section or if the salt section had been shortened at the top by solution".

The writers (1977, p. 11) make the following statement regarding their discussion of the production history: "It is apparent in retrospect that there are several well defined, if unintentional, stages in the development of this brine field, namely:

1. 1943 - 1944: drilling and completion of wells 1 through 20 around the periphery of the island. All of these wells were completed and developed as single cavity wells until coalescence into minor galleries.
2. 1948 - 1950: drilling and completion of wells 21 through 42 around the remaining periphery of the island and as offsets equally spaced within the peripheral wells. These wells were cable-tool drilled and completed by the conventional method as single cavity wells; however, as coalescence of the individual cavities formed the North and Central Galleries, these wells, as well as those drilled in stage 1, were converted to either water-inlet or producing wells employing pumps. Most of the conversion to gallery production was accomplished in the early 50's, particularly for wells in the North gallery where there was evidence of coalescence as early as 1952.
3. 1956 - 1961: drilling and completion of wells 43 through 60 as further offsets in both galleries. These wells were drilled and completed employing modern techniques including hydrofracing close to the base of the Unit B salt.
4. 1961 - 1963: abandonment of many of the wells drilled in stages 1, 2, and even 3. Wells drilled in stages 1 and 2 were abandoned because of their costly maintenance, compared with the efficiency of wells in stage 3. These wells were abandoned because collapse of insoluble material interbeds or from the roof of the cavity disrupted and damaged the casing and tubing and interrupted production. The advent of hydrofracing and the undercutting technique circumvented this problem. The history chart shows that some of the wells drilled in stage 3 had been abandoned by 1963 since they became involved in these 'mature' cavities and were unserviceable.
5. 1959 - 1971: water injection restricted almost exclusively to wells 43, 44, 67, 68 and 69. Wells 44, 67 and 68 lie within 400 feet from the pinchout axis (well 68 is actually on the axis); well 43 is 800 feet away from this line and in the centre of the

> area of localized subsidence which subsequently developed over the northern gallery; only well 69 is over 1500 feet away from the pinchout axis and practically outside the area of localized subsidence which developed over the central gallery".

The pinchout referred to above is dealt with in detail in 4.3.1. The production ascribed to each of the 5 wells to which water injection was restricted since 1959 is listed in a table.

The fact that well 69 with the highest production lies in an area with virtually no subsidence raises some questions as to the assumption "that dissolving of salt in the area of a well was proportional to the quantity of fresh water injected in that particular well". This is definitely not the case near well 69, and near well 68 on the pinchout axis.

Apparently, fresh water could travel over long distances through salt-free roof strata, and the principal salt solution may have taken place near production wells completed in stage 4. This means that the brine production figures of each well indicate more realistically the solution pattern in the brinefield.

The writers comment as follows on "the effects of each one of the development stages on the extraction of the Unit B salt and on the subsidence of the overlying rock."

Stage 1.

"Operation of the single-cavity wells of stage 1 around the island and efforts to coalesce their cavities by casing-injection operation gave rise to a series of cavities which effectively removed roof support over a larger area than if more cylindrical cavities had been formed".

The writers elaborate on casing injection as follows: "Injection of water down the casing and production up the tubing of a single-cavity well (is) recognized to accelerate connection of cavities of adjacent wells into a group or gallery of two or more wells. This in turn yielded increased productivity since the new gallery could be produced and fed at the base through tubing of the feed (w) or producing well."

The assumption that freshwater injection to the base of the salt has the postulated effects appears questionable; LANDES and PIPER (1972, p. 18 ff.) may be quoted: "Conventional wells...Casing was set at the top of the salt, and a string of tubing lowered to the bottom of the salt section to be brined. This method of operation, wherein water pressure at the surface provides the energy to lift the resulting saturated brine back to the surface, is referred to in England as "forcing".

"Forcing requires a pressure-tight cavity, a condition usually prevailing in the early life of a well. It was soon learned that introduction of the feed water down the casing annulus ("casing injection") produced brine at a high efficiency because the system was operating by gravity segregation wherein the fresh water was floating on the top... It was also found that this method caused the highest rate of salt extraction at the top of the cavity immediately under the roof, resulting in roof collapse early in the life of the well with attendant problems of tubing failure and repair expense."

"Due to greater dissolution of salt at the top of the cavity, where lighter undersaturated water accumulated, the cavity in near-horizontal beds developed a conical or morning glory shape. In time the fringes of the morning glories in adjacent wells would coalesce at the top."

There can be hardly any question as to the effects of roof collapse early in the life of the Grosse Ile wells: the fresh water floating on top of the brines in the cavities gained access to higher salt beds which were preferably dissolved. The situation soon became similar to that described in 6.3.5 for the Sandwich brinefield: fresh water, injected in quantities exceeding those of the produced brine by 5 - 10%, had uninhibited and uncontrolled access to the roof salt beds.

The reader is referred to 6.3.4, specifically to the quoted description (LANDES and PIPER, 1972) of "the mechanism known as bulking"; undercutting of large areas by morning glories resulted in well connections across the roof or even in the overlying rock through bed partings; some wells drilled near conventional wells encountered cavities at the top of the salt bed. The quoted description of progressive caving or stoping speaks for itself.

The accelerated connection of the morning glories of single cavity wells into a group of two or more wells is to be considered with respect to the horizontal dimensions and the strength of the roof strata. According to NIETO-PESCETTO and HENDRON (1977, p. 7), "the middle 370 ft. section (of Salina) tends to contain interbeds of forms of calcium sulfate (anhydrite and gypsum), and the lower 270 ft. are definitely argillaceous."

"Descriptions of a continuous core (core No. 2) by T.B. PIPER (1972) indicate that many of the dolomite layers are massive although fractured. This is an important consideration because the presence of these fractures lowers estimates of mass strength of the dolomite and supports concepts of continuous circumferential fractures which are induced by localized subsidence."

The latter statement is definitely inconclusive with regard to the roof strata of the Grosse Ile cavities. If fractures can be detected in cores, such fractures tend to run in two mutually perpendicular directions. As soon as underground subsidence commences, roof sagging results in widening of existing fractures, and there is no need for inducing fractures.

Depending on the thickness of the fractured roof beds, roof failure may indeed occur in the very early life of a cavity. The existing fractures join to form circumferential fractures at or near the fringes of the morning glories.

This mechanism has been observed in thousands of cases in salt and potash mines under comparable roof conditions, see I/4.5.3 and I/5.3.2.

Primary consideration is to be given to the fact that lateral constraint is removed from roof strata which fail at or near the fringes of advancing morning glories; the effects are similar to those observed around surface craters, no matter whether the craters are manmade (open-cast mines or quarries) or whether the craters develop as a result of underground extraction of mineral beds.

The writers (1977, p. 14) refer to a "diagramatic NE-SW cross section across Hennepin point showing probable effects of development of brine field or disruption of overlying beds."

The distance from the outer end of the morning glory of well 20 to the corresponding point of well 12 is approximately 2000 ft. i.e., about twice the thickness of the overlying rock. It is important to note that the diameter of the bowl of localized subsidence which developed at the surface was about 1800 ft. - a value very similar to the assumed diameter of "the most heavily produced area".

These statements are grossly misleading for the following reasons: (1) The writers refer to stage 1 i.e., to the years 1943-1944. Only the wells 12 and 20 were operated since 1944 as single cavity wells until 1948 and 1950, respectively, when the fringes of their morning glories coalesced at the top with adjacent wells.

The adjacent wells shown in the cross-section were drilled in stage 2 or stage 3.

Well 25 was completed in 1949 or in 1950, depending on whether the year shown on the production history chart or the year shown on the cross-section is correct. According to the latter figure, the well was operated for 11 years as inlet well.

According to the production history chart, the well has been inactive since 1961; in 1968, "logging showed open cavity, or evidence of cement loss when plugging back" above salt 2 in the Salina F Unit. As early as 1960, "salt or dolomite partings" occurred at the salt 3 level (Salina D).

For this reason the well was retired in stage 4 as quoted above.

The writers refer to well 25 "as an example of a typical stage 2 well. Top injection led to rapid coalescence of the individual cavities at the top of the salt creating the desired galleries. As a result, however, roof support was effectively removed in an erratic manner and a large part of the lower salt was left untouched. It is not surprising that many of the wells of stage 3, drilled 6 - 17 years after the completion of wells of stages 1 and 2, encountered complete salt sections without any indication of cavities."

Well 34 of the cross-section appears to be another typical stage 2 well. Apparently, it encountered "salt or dolomite partings" in the Salina B salt. It was completed in 1949 or in 1950 and was operated for 3 or 4 years; the data again differ in the production history chart and in the cross-section, respectively.

Bed separation apparently occurred in 1953 in the Salina C Unit, and again in 1962 at a slightly lower elevation. The cross-section shows more bed separations above the salt 3 in the Salina E, but no date.

Well 43, located near the centre of the North gallery, was completed in stage 3 (1956); since 1960, bed separations were detected at successively higher elevations. The well was abandoned in 1968. In 1969, "logging showed open cavity or cement loss" and evidenced bed separations up to the top of the Sylvania sandstone at the depths of approximately 250 feet.

(2) The distance between the outer morning glories of wells 20 and 12 may have been approximately 2000 ft.

However that distance is not the span of the future North gallery; the maximum span was approximately 1600 feet and developed during stage 5 of the operation of the North gallery. "Hydrofracing close to the base of the Unit B salt: was not employed until 1956; apparently, well 43 was the first one to be developed in this way.

(3) The bowl of localized subsidence above the North gallery was not about 1800 ft. in diameter. Apparently, the writers refer to what they term "generalized subsidence". They also postulate that areas outside the brinefield are not affected by surface subsidence; in that case, the maximum span (diameter) can apply only to "generalized subsidence". Localized subsidence at increasing rates indeed occurred only in central areas of the brinefield, but not before 1969, as shown in the following discussion of quotations from NIETO-PESCETTO and HENDRON (1977).

Stage 2.

"The offset wells of stage 2 caused further removal of support within the area delineated by the peripheral wells". Parts of the writers; statements are quoted above with reference to wells 25, 43, and 34 in the North Gallery. The rest of their statements reads as follows:

"Four exploratory holes, X-1 through X-4, were drilled in 1969 over the centre gallery. Although the base of the B salt was found intact, it is difficult to determine if these boreholes penetrated the entire salt section or if the salt section had been shortened at the top by solution. Many of the adjacent wells were drilled before the advent of logging, thus neutron logs are not available for comparison with those on the exploratory boreholes. However, these exploratory holes did fail to show any evidence of appreciable open cavities within the Unit B or in the overlying rock section".

"The conversion from single well operation to gallery production in the early 50's occurred when the cavities merged. This had as one effect the reduction of the effective roof support over a relatively large area. Modern completion techniques (undercutting) improved the efficiency of the operation and enhanced dissolving at the bottom of the salt, but by this time the formation of conventional roof-connected cavities had probably already removed a large portion of the salt near the roof."

"Dissolving near the top of the salt probably continued even after the advent of undercut connections (all wells 43 and up). This could be accomplished when an undercut channel intersected a conventional well cavity even if abandoned and undersaturated brine rose to the top of the cavity and was free to migrate - it would then cause further extraction near the roof. Unless feed wells were tubed or cased to the bottom of the salt, this action would be operative even with modern wells. This would require regular logging and rework on the part of the operator".

In their quoted assessment of the underground solutioning process, the writers completely ignore the fact that early, progressive roof failure allowed undersaturated brine to rise above the top of the Unit B salt and to dissolve salt at higher elevations, similar to what happened in the Sandwich brinefield, see section 6.3.

As the writers put it: "the conversion from single well operation to gallery production in the early 50's" resulted in "reduction of the effective roof support over a relatively large area" around the periphery of Grosse Ile. All of the wells 1 through 42 drilled during stages 1 and 2 were drilled around the periphery of the brinefield. Evidence of coalescence of these wells was not found until 1952; hydrofracing close to the base of the Unit B salt was not employed until 1956. Thus it is safe to assume that fresh water gained access to salt beds at higher elevations around the periphery of the brinefield when individual morning glories connected.

As quoted above, the writers assume that dissolving near the top of the salt continued after the advent of undercutting, i.e., after 1956. Since it appears safe to assume that fresh water had access to overlying salt beds there is no justification for the assumption that only Unit B salt was dissolved at Grosse Ile. The quoted reasons for the abandonment of many of the wells during stage 4 (1961-1963) are re-emphasized; collapse of insoluble ledges or roof collapse disrupted and damaged the casings.

NIETO-PESCETTO and HENDRON (1977, pp. 16/17) place particular emphasis on the discussion of what they call stage 5 in the operation of the Grosse Ile brinefield. In fact, however, stage 5 (1959-1971) includes 2 years of stage 3 and all of stage 4 (1961-1963).

"Continued operation of inlet wells near the pinchout (see 4.3.1) deserves special consideration. The existence of the pinchout causes the following:

1. Reduction of available salt volume per unit of brine field area.
2. Redirection of dissolving away from its axis because the roof slopes upward away from the axis and the undersaturated brine would be free to migrate updip along the sloping 'roof' due to gravity buoyancy".

With reference to Fig. 4-5 it is stressed that the Silurian solution feature, called pinchout by the writers, exhibits a N-S axis (wells 66, 68, 33, 11) and an E-W axis (wells 36, 49, 43).

In the North gallery the continued operation of water inlet wells near the N-S axis and along the E-W axis, specifically well 43, results in updip flow of freshwater both to the north and south periphery of the brinefield. The area around well 34 where the North gallery sinkhole formed received updip flow from both axes, i.e., from the north as well as from the south. It appears that the writers overlooked the significance of their own statement.

The situation in the Central gallery is different because there is no E-W pinchout axis developed; on the contrary, a comparison of Figs. 4-4 and 4-5 indicates increased salt thickness north of the continuation of the E-W pinchout axis of the North gallery. This means updip flow of freshwater from the N-S pinchout axis to the south, i.e., again to the area where sinkholes developed.

The writers postulate an entirely different development: "the result of the effects discussed above is to accomplish much more complete extraction of the available salt adjacent to the pinchout axis than in areas where the salt is thicker. This concentrated dissolving also increases the probability of large unsupported spans immediately adjacent to the axis. Continued operation of inlet wells near the pinchout made the above results much more pronounced, i.e.: they dissolved most of the salt near the pinchout axis and extended the area of inadequate roof support into what became the areas of localized subsidence".

TABLE 6-I

Salt production ascribed to selected wells, Grosse Ile brinefield (NIETO-PESCETTO and HENDRON, 1977).

Total production in millions of cubic feet of dissolved salt calculated from quantity of fresh water injected.

Well No.	Production well from	Production well to	Water inlet well from	Water inlet well to	Ascribed salt production millions of ft.^{3}	Gallery
43	56	59	59	68	29.6	North
44	56	58	59	69	31.7	North
67	--	--	64	70	33.2	Central
68	70	71	65	69	17.0	North
69	--	--	64	71	34.8	Central

"It should be noted that wells 43, 35A, 44, 68, 37, 67, 53 and 32 were inlet wells which were located close to the axis of the pinchout and that these wells accounted for production of about 180 million ft.^{3} of salt. This was almost one-half of the total salt dissolved in the North and Central galleries".

As emphasized previously, the location of salt solution by water injected into specific wells depends primarily on the question where the fresh water makes continuing contact with salt beds; if the morning glories of individual wells cause roof failures which enable water flow in roof strata, no salt solutioning takes place near injection wells, but rather near production wells where the heavier, more saturated brines are pumped from the bottom of the cavities.

It appears definitely inconclusive to assume that almost one-half of the produced salt was dissolved near the N-S pinchout axis. The effects of updip solution discussed above provide another strong argument against preferred solutioning near water inlet wells.

The writers emphasize specifically that "wells 43 and 44, both in the North gallery, were inlet wells for about 10 years; fresh water injected at these locations could have dissolved" the volumes of salt listed in Table 6-I. "These wells were two of the largest producers and were ultimately within the location of the sinkhole which formed in the North gallery".

As stressed above, these two wells should not be called salt producers; updip flow from these wells may have contributed to the sinkhole formation. However, at least well 44 is definitely not located "within the location of the sinkhole".

"As localized subsidence became more pronounced over the North gallery, injection into these wells was discontinued. Well 43 was abandoned in 1968 and well 44 was terminated in 1969 in an effort to shift salt production away from the assumed centre of the North gallery, and hence to arrest further development of the bowl of subsidence".

The geometrical centre of the North gallery need not to be assumed, but can be determined; the writers apparently refer to the assumed centre of salt solutioning, i.e., to the area where the largest quantity of salt was removed from an area unit.

Their assumptions are based on quantities of water injected into each well; this assumption is questionable, as shown above. Equally questionable is the expectation that the attempted shift of salt production away from the assumed centre of solutioning could possibly arrest the further development of the subsidence trough. The facts prove this point:

"Whereas this was a sound measure, it did not have the expected results as evidenced by the eventual formation of the sinkhole over the North gallery. The large production ascribed to these two wells and the occurrence of a sinkhole which was virtually centered around well 43 are strong lines of evidence indicating that a large portion of roof support had been removed by the time these wells were terminated".

The different definition of the sinkhole in the quoted statement should be noticed. The actual sinkhole with the postulated chimney down to the B salt formed at 2311 34; well 43 may be considered as the centre of what is called localized subsidence in the rest of the publication.

"Similar reasoning can be applied to wells 27, 32, and 60 in the Central gallery. These three wells are located within 100 feet from the approximate limit of the surface cracks that surround the sinkholes over the central gallery. These wells were terminated even earlier than wells 43 and 44. Wells 27 and 32 were terminated as early as 1961 and well 60 was abandoned in 1964. However, their combined production was 50.4×10^6 ft.^{3}; they also had a strong effect in removal of roof support in the central gallery".

This writer wishes to emphasize that wells 29, 50, 54, and 56 were operated as production wells in the sinkhole area; wells 50 and 54 were abandoned in 1960 after less than 2 years of operation. This leaves no doubt of early roof failure problems in the sinkhole area.

"Detailed examination of well logs also turned up other observations which are worthy of note. Because undersaturated brines probably moved up behind uncemented casings of the initial wells and through channels behind cemented ones, dissolving probably took place in salt layers Nos. 3 and 2.

"As early as 1958, heavy cement losses to salt No. 3 were recorded when well 19 was plugged back to 850 ft. Losses were also recorded opposite salt No. 3 (July 1959) in well 49 through a leak in the casing. No fluid losses to salt No. 2 were recorded; however, it is very likely that such losses did occur."

"In 1968, wells 43, 45, 56, and 25, which had been plugged back to the bottom of salt No. 2, showed leaks at the surface; later, surveys indicated that leakage was taking place through breaks in the casing above a depth of 800 ft. These casing breaks, derived from bed partings, could be interpreted, at least in part, as evidence of dissolving of salt No. 2".

"Casing partings at depths less than 800 ft. can also be interpreted as evidence of propagation toward the surface of disturbances in the overburden rock. The casing breaks which progressed upward with time in well 43 are illustration of the deterioration of the rock toward the ground surface with time. Similar evidences of casing breaks or open cavities were found in the logs and histories of wells 2, 25, 34 and 12".

The quoted observations fully confirm early, progressive roof failure in the Grosse Ile brinefield, similar to what happened in the Sandwich field at Windsor. There is absolutely no justification for the assumption that only Unit B salt was dissolved, as postulated in the chimney hypothesis.

Salt dissolution at higher elevations and bed separation began around the periphery of Grosse Ile when the morning glories of individual wells coalesced; considerable subsidence of the whole overburden became inevitable when the initial morning glories became interconnected across the island.

6.4.2.4 Surface subsidence measurements

An extremely important difference between the subsidence measurements above the 3 brinefields discussed by NIETO-PESCETTO (1977) is to be stressed in the first place.

At Windsor, the reference points were established on structures (buildings) in the brinefield; as emphasized in 6.3.1, the surface subsidence data are not necessarily indicative of subsidence due to salt extraction. At least many minor vertical displacements may reflect lateral displacement of soft soil. Displacements of buildings founded on pilings down to the bedrock reflect subsidence of the bedrock surface.

At Grosse Ile, "many of the reference points are attached to well casings; in that the casings are cemented or otherwise bonded, the readings are considered to reflect movements of the rock surface, about 100 ft. below the ground surface" (NIETO-PESCETTO and HENDRON, 1977, p. 18). The writers fail to indicate the reference points which are considered to indicate subsidence of the bedrock surface.

The man-made overburden apparently had considerable strength, see 6.4.2.2. Monuments eatablished on that overburden should not be compared with reference points on well casings.

Furthermore, the writers (l.c., p. 17) refer to "uncemented casings of the initial wells", probably the first 42 cable-tool wells drilled around the periphery of the island; this raises the question if reference points established on such casings were included in the construction of subsidence contour maps.

The writers provide no information on the reference points established in the third brinefield, the Wyandotte North Works. In all probability, most of the building were founded on pillars. The writers also fail to give any information on the area covered by brining operations.

For this reason the question why "sinkholes have not occurred" in this brinefield (l.c., p. 6) cannot be discussed on the basis of "documented behavior"; the writers' failure to provide documentation is considered as a serious shortcoming.

The writers' analysis of subsidence data includes "time versus settlement plots for each monument and settlement maps" (contour maps); examples are shown to provide "some explanation on the construction procedure used in making these maps".

(1) "Points on the time-settlement plots for the individual monuments were connected by a continuous line; a smooth curve was then fitted through this trend. For the most part, the fitted curve did not deviate more than ± .025 feet or 0.3 inches from the plot; this deviation is believed to represent the accuracy of the surveys and the quality of the monument system in representing the subsurface changes taking place. Settlement values for the maps were than obtained from the smooth line".

(2) "Resolution of the time-settlement curves is about 1 month; i.e.: one month in the graph is represented by approximately 0.02 inches. It is difficult to determine if a reading was taken, say, at the end of March or the beginning of April. Thus, the beginning and the end of the periods shown in the subsidence rates plots may be off by about

a month. In view of the time required to perform precise level surveys of an area this large, this is not considered to be detrimental to this study".

(3) "It is sometimes rather difficult to indicate by a precise date the occurrence of even a surface collapse, as in the case of the North gallery sinkhole, because the activity may be progressive and extend over months or even years. For reasons of consistence with previous work, January 1971 is considered here as the month of collapse at the surface or beginning of cratering for the North gallery sinkhole and April 1971 as the corresponding date for the Central gallery. It is quite probable, however, that the actual surface collapse date for the North gallery could be two or three months earlier".

The latter statement appears rather strange as there were only 6 reference points available in each of the two galleries until 1959.

Comparing the great numbers of reference points surveyed in other brinefields, and on Grosse Ile since 1959, one cannot escape the conclusion that little effort was made to establish reliable information on the overburden behavior during the first 15 years of operation of the brinefield.

As a consequence, the previous history of settlement for all but 12 reference points is considered as unknown until 1959. The writers merely make assumptions which may or may not be correct; some of the assumptions are to be discussed in detail as they appear questionable for reasons to be given.

It should be noted that the survey of 12 reference points on Grosse Ile started in 1954, the year of the formation of the so-called Windsor sinkhole. Up to 10 years of possible settlement are missing even for the few reference points listed in Table 6-II.

These facts are considered as very detrimental to the study under discussion; its objectives, see 6.4.2.1, could hardly be achieved if indeed basic assumptions are questionable or erroneous.

(4) The previous work referred to includes the report by LANDES and PIPER (1972) which reads as follows: "Solution mining had been in operation at Point Hennepin for nearly 20 years when, in November 1969, cracks first were observed at the surface above the North Gallery.

One year later settling became noticeable, resulting in pipeline breaks. On 9 January 1971 cratering started, and several months later the sinkhole reached its present configuration. On 28 April 1971 collapsing started above the Central Gallery about one-half mile away, without prior surface cracking or pipeline failures. The result was a second sinkhole, this one with a satellite. The Central Gallery cratering also took several months to reach its present size and shape".

"A line of zero cracks was drawn around each sinkhole, enclosing the area of surface activity. Each lies within the underlying gallery boundaries, and had not changed appreciably at the time this was written, approximately a year later. Other areas of the brine field are not involved in the activity and operations continue undisturbed. Observations of precise level elevation monuments indicate stability has been restored to the disturbed area, duplicating that achieved at Windsor subsequent to 1954".

In the strongest way possible must be emphasized here that stability was not restored at Windsor, see 6.3.7; the brinefield subsidence continued and reached maximum values up to 1.5 m over the decade following the formation of the so-called sinkhole. Such behavior expected from the subsidence characteristics dealt with in Chapter 7.

Furthermore, the Windsor brinefield as well as those on Grosse Ile were abandoned. It cannot be expected that stability was restored to the two galleries on Grosse Ile.

(5) "Since it was necessary to compare the amount of settlement during the five years before collapse for the Grosse Ile sinkholes with that for the Windsor sinkhole, the settlement curves for some of the wells of the North gallery were extraploated from the last reading - September 1970 - to December 1970, the end of the selected five year period".

The writers appear to assume that the surface collapses on Grosse Ile terminated the process of overburden subsidence. It is strongly re-emphasized that the formation of a sinkhole is definitely not the final episode of subsidence, even if brining operations are terminated. The reader is referred to 6.1, and to the other case histories dealt with in this text.

Due to the lack of measurement data, the writers resort to subsidence-rate contour maps. As an example (l.c., p. 20), they show a typical map "which was constructed to depict subsidences that occurred during 1961 and 1962. It is presented to show that as early as 1962, and most likely earlier, two well defined bowls of settlement had developed with centres generally indicative of the area where the sinkholes ultimately formed. At this time, the maximum rate of subsidence was about 0.6 in./yr (one-half inch) in the Central gallery and about 0.3 in./yr (one-quarter inch) in the North gallery".

"It should also be noted that even at this early date there was indication of asymmetry in the contours of the North gallery in that the contours close to the pinchout were steeper than those away (northward) from it. Throughout this paper the side of the bowls of subsidence adjacent to the salt pinchout will be referred to as either the inner or downdip side and the opposite side will be referred to as the outer or updip side".

These statements regarding the asymmetry of the subsidence contours cannot be accepted. The writers consider the so-called pinchout as instrumental in subsidence with attendant sinkhole formation. These matters require a detailed discussion.

In the first place, it is re-emphasized that only 6 reference points in each gallery were surveyed from 1954 to 1959, see Table 6-II.

The 1961-1962 subsidence rate contour line shows zero subsidence at well 34 where the North gallery sinkhole formed. Wells 13, 14, and 16, at the western periphery of the island, are shown outside the subsiding area. Well 15, with the highest subsidence rate at the western periphery, was a single well from 1944 through 1946, and a production well from 1947 through 1958; this is the apparent reason why the subsidence rate at this well was still considerable during the 1961-1962 period, although the well was inactive after 1958.

Secondly, the development history of the North gallery must be taken into consideration in any assessment of overburden subsidence near Hennepin Point, north of the ponded area. Only the wells 12 through 20 were in operation since 1943 in what later became the North gallery.

TABLE 6-II

Correction of cumulative subsidences, Grosse Ile, Dec. 1954 - Dec. 1970. Only 12 reference points were surveyed, until 1959. Subsidences in hundredth of a foot (after NIETO-PESCETTO and HENDRON, 1977). Data in brackets are estimated from the respective contour maps.

North gallery

Well No.	14	17	19	20	21	23
Year of completion	'44	'43	'43	'43	'49	'49
Operated as single well until	'46	'50	'46	'50	'51	'53
Measured subsidences						
'54 - '59	22	12	32	25	30	36
'60 - '65*	0	6	9	12	9	30
'66 - '70	17	10	46	26	35	87
Total subsidence '54 - '70	39	28	87	63	74	153
Shown on map	40	25	89	58	64	136
Difference	+1	-3	+2	-5	0	-17
Difference as mm	+3	-9.1	+6.1	-15	0	-51.8

South gallery

Well No.	8	9	30	31	37	40
Year of completion	'44	'44	'49	'49	'50	'50
Operated as single well until	'50	'51	'57	'52	never	never
Measured subsidences						
'54 - '59	6	6	0	6	5	6
'60 - '65*	33	30	0	24	18	30
'66 - '70	26	15	11	(120)	0	20
Total subsidence '54 - '70	65	51	11	150	23	56
Shown on map	52	35	25	(230)	17	43
Difference	-13	-16	+14	+80	-6	-13
Difference as mm	-4	-4.9	+4.4	+24.4	-1.8	-4

*Calculated from subsidence rates 1961 - 1962 (l.c., p. 20)

The production history chart (l.c., p. 12) shows:

In 1947, wells 14, 15, and 19 had developed into a minor gallery; well 19 was used as water injection well until 1959.

In 1949, wells 12 and 13 had merged; well 12 served as water injection well until 1951 when both wells became production wells. This indicates merger with the first minor gallery. The wells were inactive since 1954.

In 1950, well 16 coalesced; it was used as production well until 1958.

In 1951, well 17 had merged; it was used as water injection well until its retirement in 1961.

The span of the North gallery evidently is much smaller than the span of the Central gallery; this is the reason why the subsidence rate above the North gallery is smaller, although it was "the primary source of salt before 1960".

It should be noted that two separate areas of localized subsidence developed in the Central gallery; the contours in both areas are much steeper than those of the North gallery. The sinkholes formed in the western area around well 29, including wells 50, 54, and 56; all these wells were production wells for various periods of time prior to 1962; they were abandoned with the exception of well 56 as roof failure apparently was progressing toward the surface.

Well 51 in the centre of the second area of localized subsidence served as production well from 1959 through 1969. Both areas of localized subsidence served as production well from 1959 through 1969. Both areas of localized subsidence are elongated in the direction of the periphery of the brinefield.

The writers present several more subsidence rate contour maps for various periods of observation; the maximum subsidence rates are listed in Table 6-III.

According to the writers, "it is interesting to note that some upward movements were detected over the pinchout area" for the 1966-1968 period. "These positive values have been observed in settlement readings made at other brinefields and require an explanation in terms of rock mechanics. However, no explanation is attempted here because it is felt that more detailed information is needed about surveying procedures and benchmark control. Nonetheless, this situation serves to illustrate the markedly different behavior between the galleries and the pinchout area".

TABLE 6-III

Maximum surface subsidence rates, Grosse Ile, for various periods of time (NIETO-PESCETTO and HENDRON, 1977)

Time period	North gallery	Central gallery
	In./yr	In./yr
1961 - 1962	0.3	0.6
Dec. 1966 - Dec. 1968	1	2
Apr. 1969 - Apr. 1970	18	4.8
Apr. 1970 - Apr. 1971	sinkhole started January 1971	sinkholes started April 1971

The reader is referred to Chapter 7. Upward movements have been measured at numerous occasions. Abutment zones of extracted areas tend to show small amounts of upward movement because of failure of bridging overburden formations; abutment loads disappear when the overburden is fully supported in the extracted area.

However, as emphasized in 6.1, unless control surveys start contemporaneously with the start of extraction, any appraisal of the surface effects or the direction of solutioning is extremely difficult as it has to be based on assumptions.

CHAPTER 7

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7 CONTROLLED OVERBURDEN SUBSIDENCE

7.1 SUBSIDENCE DUE TO PARTIAL EXTRACTION OF SALT DEPOSITS

7.1.1 Subsidence characteristics

The prediction of overburden subsidence due to mineral extraction is a science in itself, dealt with in numerous publications and textbooks. Most writers are mine surveyors who were active in this special field in various mining districts and collected ample measurement data to support their predictions of subsidence under comparable conditions. In recent years, with the advance of computer techniques, it became fashionable to predict surface subsidence on the basis of theoretical assumptions. Some published hypotheses applied to the extraction of salt and potash beds are questionable as they are based on erroneous assumptions.

Figure 7-1 shows some basic characteristics of overburden subsidence caused by underground extraction of a bed of minerals (after PANEK, 1970).

It is impossible to present here any detailed review of subsidence characteristics under various geological conditions; some of PANEK's statements are quoted to emphasize important points. Although PANEK refers mainly to coal mining, his statements are applicable to the extraction of flat-lying salt and potash beds because of similar overburden behavior: in both coal and salt mining, overburden formations are made up of sedimentary formations. As a matter of fact, coal deposits and salt deposits quite frequently are mined in the same basin of sedimentation.

One important difference should be borne in mind: in coal mining districts frequently several coal beds are present in the stratigraphic column; mining the deepest bed in the column causes overburden subsidence and may alter the behavior of some or all of the overburden formations. For this reason, caution is necessary when effects of the extraction of several coal seams are compared with effects of the extraction of a single salt or potash bed.

PANEK's abstract reads as follows: "Subsidence of the earth's surface is the inevitable result of extracting a substantial volume of mineral material from beneath the surface. The subsidence profile has the general shape of a basin, along which any given point may be displaced both vertically and horizontally. Since the displacement is not the same for all points, surface structures may be subjected to

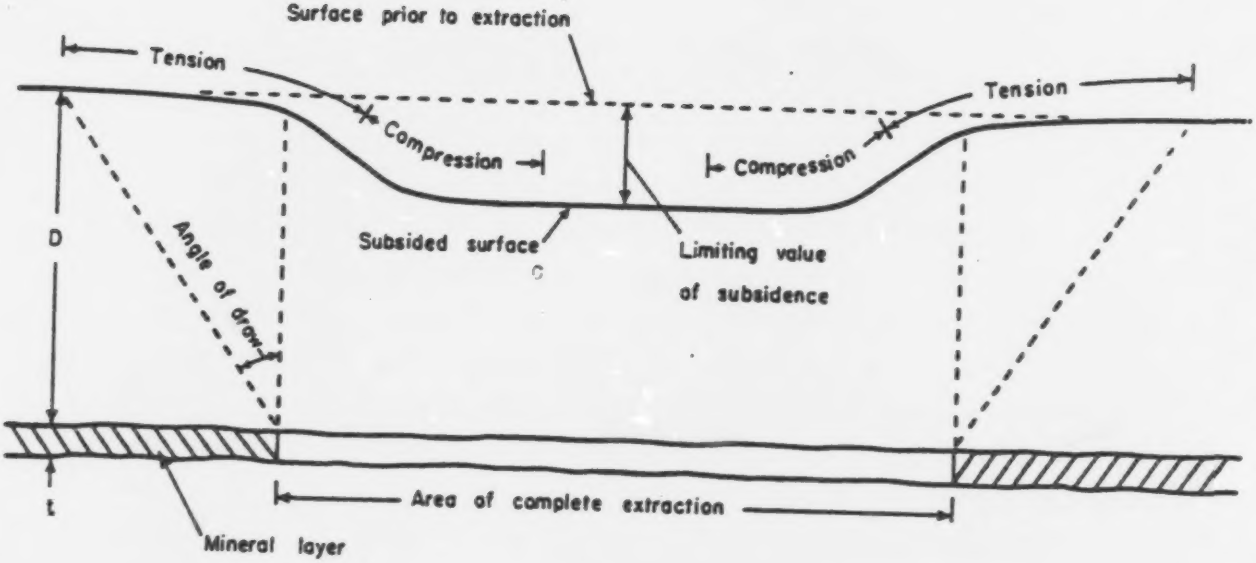


Fig. 7 - 1: Subsidence characteristics (PANEK, 1970)

differential settlement, tilt, and horizontal deformation. The amount and distribution of these distortional phenomena depend on the geometry of the extraction zone and on the structural characteristics of the undermined rock strata."

"Both analytical and experimental approaches have contributed to our understanding of subsidence mechanics. Only actual field measurement, however, can provide numerical values for the important parameters, knowledge of which is prerequisite to rational design and control".

With reference to Figure 7-1, PANEK points out: "Subsurface extraction of a mineral material creates a void, which results in a lowering of the earth's surface above the void. Measurements show that the affected surface area or subsidence basin exceeds the area of extraction, even though this may not be apparent to the eye. The 'angle of draw' from the extraction boundary to the outer limit of surface subsidence may be as much as 45° from the vertical, depending on the structural characteristics of the rock strata overlying the area of extraction. It is obviously difficult, even by highly precise methods of measurement, to detect where the asymptotic subsidence curve reaches exactly zero vertical displacement. The angle of draw determined by other than a precise surveying method is much less than the true value. Some observers have reported angle of draw values based on visual observations, which more likely correspond to the outer limit of surface cracking, or to the boundary of an obvious slump zone".

It may be pointed out here that most European writers prefer the use of the supplementary (to 90°) angle to the angle of draw, i.e., the angle between a theoretical horizontal line and the outer limits of both underground extraction and surface subsidence, respectively. This should be borne in mind in studies of Euorpean literature on subsidence caused by subsurface extraction.

"Many measurements made above coal mines in the coal fields of the U.K. (National Coal Board, 1966) reveal that the limiting value of subsidence is reached when the span of the void (the area of complete extraction) exceeds 1.4D (D - depth) and that the limiting subsidence amounts to about 0.9t (t - seam thickness). The depth of the subsidence basin can be reduced by decreasing the span of the void. Above these coal mines for example, the maximum subsidence is only about 0.45t if the span of the void is about 0.7D".

"Any surface subsidence basin (Fig. 7-1) consists in general of an outer belt or zone of horizontal tensile strain, surrounding an inner zone of horizontal compressive strain. If the span of the underground void is great enough (1.4 D for a 5 ft. seam) to produce the limiting value of surface subsidence in the center of the subsidence basin, then this comprises a third (and lowest) zone, in which there is no horizontal strain. In other words, the tension zone and the compression zone together comprise a disturbed zone of transition between the central relieved but fully subsided zone (if the subsidence basin is fully developed) and the as yet undisturbed ground surface surrounding the subsidence basin."

At this point of PANEK's description, it may be emphasized: above salt and potash mines with pillars left for subsidence control, the surface subsidence trough (this term is given preference over "basin" as used in the quotations) cannot reach the limiting value until the openings created by extraction mining are closed by creep of the surrounding salt. As shown in Volume 1 of this text, the time required for creep to close mined-out panels completely may amount to several years, several decades, several centuries, or several millenniums - depending on various circumstances to be dealt with in more detail in following sections.

Figs. I/5-11 and I/5-13A show the surface subsidence characteristics also valid for underground subsidence troughs, except for statements regarding the limiting value of subsidence. This also holds true for the following continuation of quotations from PANEK (1970):

"As the subsidence basin grows in area, owing to the progressive extraction, more and more surface structures in effect enter and pass through the disturbed transition zone, where they are subjected first to a stretching and then to a compressing. Considering the profile of the subsidence curve, Fig. 7-1, it can be seen that while the surface structure is in the tension zone it is also subjected to an increasing tilt, due to the slope of the ground surface, and to an upward 'bowing' or flexing, due to the curvature of the ground surface; in the compression zone, a surface structure is subjected to a reverse flexing with decreasing tilt."

"In order to evaluate the effects of surface subsidence, therefore, one must consider not only the effect of the vertical displacement, which is the most obvious characteristic of subsidence, but also the effects of horizontal strain, tilt, and curvature. These components of displacements and distortion are illustrated in Fig. 7-2".

"In order to 'live with' subsidence, or control its location, or limit its magnitude, one must be able to estimate or predict the numerical values of maximum vertical displacement, maximum horizontal strain, maximum tilt, and maximum curvature for a given depth, thickness, length, and width of extraction volume; one must be able to draw contour lines over the extraction area to indicate the expected amounts of vertical displacement, horizontal strain, tilt, and curvature at any location in the subsidence basin and for any stage of extraction."

"British and European experience (in coal mining, author's remark) show that remarkably consistent relations can be found among the geometric parameters (depth, width, thickness, span of the void) and the significant subsidence variables (displacement, tilt, strain, curvature). It is not to be expected that numerical values found in one region will hold true in another, where different strata overlie the extracted layer, nor that the numerical values will be the same for a 5-ft coal seam as for a 15-ft salt bed. The point is, however, that one can expect to find consistent relationships if one makes measurements of actual subsidence behavior."

"Theoretical analyses have been made by many authors to describe the structural behavior of the overburden by the classical methods of theoretical elasticity, viscoelasticity and plasticity, by soil mechanics principles, and by treating subsidence as the stochastic (probability) motion of particles in a granular medium. These approaches have contributed to our understanding of the mechanics of subsidence and are capable of describing subsidence behavior in a general way, but they have not been successful in predicting the actual numerical values of the subsidence components. This is partly due to the inherent limitations of the methods of analysis, which can only handle overly simplified structural models, and partly because we have not yet learned how to quantify all the significant parameters of the geological structure".

PANEK's summary, although based mainly on experience in coal mining, is considered applicable - mutatis mutandis - to salt and potash ex-

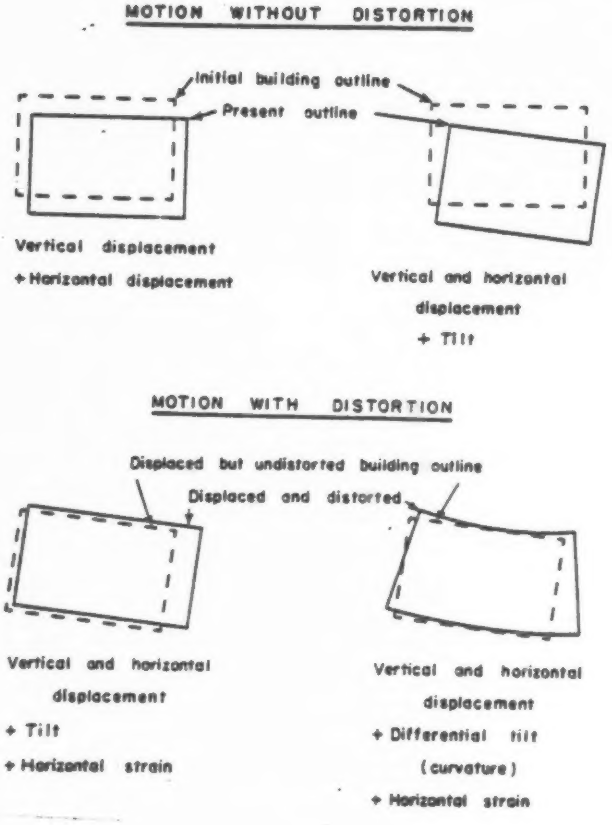

MOTION WITHOUT DISTORTION
Initial building outline
Present outline
Vertical displacement
+ Horizontal displacement
Vertical and horizontal displacement
+ Tilt
MOTION WITH DISTORTION
Displaced but undistorted building outline
Displaced and distorted
Vertical and horizontal displacement
+ Tilt
+ Horizontal strain
Vertical and horizontal displacement
+ Differential tilt (curvature)
+ Horizontal strain

Fig. 7 - 2: Subsidence without and with distortion of buildings (PANEK, 1970)

traction; it reads as follows:

"Sufficient theory and general principles are available to adequately correlate and interpret subsidence observations and measurements. From the assortment of measuring instruments that is available, a number of combinations can be formed to obtain the measurements that are needed to adequately specify the subsidence behavior. Reliable procedures are given here; more sophisticated techniques are being developed."

"For prediction of subsidence disturbances, some progress has been made in anlytical studies of the behavior of an undermined rock mass, especially by the finite element method of structural analysis, which relies heavily on the use of modern computers. This approach is handicapped by the cost and physical difficulties entailed in establishing the values of the significant structural parameters, which are the thicknesses, strengths, densities, deformation moduli and jointing patterns of the rock strata that comprise the overburden."

"Systematic progress, however, can be achieved by initiating a program of field measurements of the displacements, strains, and tilts, which accompany the progress of extraction. More subsidence data are needed in order to construct and verify theoretical structural models which can be used to predict subsidence components for geological conditions that are typical of those where extraction is being done. Data developed at any given extraction operation will not suffice to predict subsidence parameters a few miles away, without a knowledge of how to take account of changes in the structural characteristics of the overlying rocks, which is one purpose of the structural model. In this approach, measurements taken at several different extraction operations can be combined to provide a predictive capability much beyond what a single company can achieve."

"Experience shows that any company engaged in extracting minerals from the earth should conduct at least a token program of subsidence measurements, in order to protect against unexpected occurrences caused by ground movement. Interpretation of a significant ground disturbance and future stability depend in large part on the availability of past trends, which can provide a basis for judgment".

It is re-emphasized that these statements, descriptions, and conclusions apply to complete extraction of a mineral bed over a wide area according to Figure 7-1. Complete extraction "will yield the greatest mineral recovery per acre; the largest part of the subsidence zone will experience the maximum vertical subsidence but should be free of horizontal strain, tilt, or curvature; the maximum values of these components will be relatively large but will be localized along the perimeter of the extraction zone. With partial extraction, it has been found possible (WARDELL 1969) to arrange the shape, size, and spacing of panels and pillars so as to reduce subsidence to a fracture of the limiting value".

The latter concept of minimizing subsidence may be feasible in cases where the extracted mineral material and the roof and floor strata possess sufficient strength to provide structurally stable support elements (pillars) which are left for this purpose in mined-out areas.

This concept is not applicable in salt deposits.

With reference to publications by WARDELL (1968) and McCLAIN (1964), it is shown by Figs. I/5-18 to I/5-20 that the panel-and-pillar concept failed to prevent considerable surface subsidence when applied in a French potash mine. The same concept had been applied previously in German potash mines where it also failed to provide the expected structural stability.

It must be borne in mind that constant final creep closure rates develop around openings in partially extracted salt deposits. Such creep at constant rates controls the overburden subsidence.

At shallow depths, the final creep closure rates may be very small; the mine openings may remain useable for many decades, even for several centuries.

At great depths, however, the creep closure of excavations in salt deposits may be completed within less than a decade; the surface subsidence may reach its limiting value within approximately the same period of time.

This appears to constitute the main and only difference in surface subsidence characteristics when comparing coal mining (complete extraction) with room-and-pillar mining of salt and potash beds; in coal mining, the limiting value of surface subsidence may be reached within months, while it may take decades or centuries until the limiting value is reached above room-and-pillar mines in salt and/or potash deposits - depending on the creep closure rates which are allowed by any particular mine design.

In all other aspects, however, the subsidence characteristics are similar; this is to be shown by long-term measurement results.

In any evaluation of measured surface subsidences above room-and-pillar mines in salt and potash deposits; the effects of stress relief creep must be borne in mind; the depth factor D used in the foregoing quotations can be used only in cases where overburden subsidence has resulted in full pillar reloading according to depth and extraction ratio. Reference is made to respective figures, e.g., I/5-1 and I/5-2.

It goes without saying that the thickness factor t must be calculated from the extraction ratio in room-and-pillar and in panel-and-pillar mining of salt and/or potash beds; this also applies to multiple-cavern systems for storage purposes, and to mined repositories for nuclear and other dangerous wastes.

As emphasized repeatedly: stress relief creep into any such excavation is inevitable, and reloading creep cannot be prevented unless the extraction ratio is kept below any acceptable value. For these reasons, pillars designed for overburden support must be treated as effective instruments for overburden subsidence control. Under certain geological conditions overburden subsidence must be initiated for necessary control of floor deformations.

7.1.2 Purpose of surface subsidence measurements.

At the beginning of this century, field measurements of surface subsidence as postulated by PANEK (1970) became compulsory above potash mines in some German states. These state regulations were issued because of the disastrous floodings of potash mines in the Stassfurt area; the overburden collapses caused severe damage to residential areas of the city of Stassfurt.

The subsidence surveys had to be conducted at regular time intervals of a few years. Their purpose was to prove that no surface subsidence of any significance occurred above mined-out areas of potash mines, i.e., to show the structural stability of the mine pillars left for permanent support of the overburden, and to show that the overburden formations were kept in their original position.

At the beginning of this century, it was believed possible and necessary to achieve structural stability of salt and potash mines with no measurable surface subsidence occurring even above large mined-out areas in flat-lying, tabular deposits. Some theoreticians still believe in the possibility of designing room-and-pillar mines in salt deposits which are structurally stable like civil engineering structures, see 1.3.2.

The measurement results presented in the following sections show such hypotheses illusive and dangerous, and this has been known for many decades. In view of continuing efforts to publicize design principles which are based on misleading laboratory testing, particular emphasis is placed on the results of long-term surface subsidence measurements presented in the following sections. More data can be found in Chapter 2 with case histories of dangerous application of erroneous design principles which resulted in disastrous rockbursts and earthquakes.

The results of long-term surface subsidence measurements show beyond doubt that overburden settlement cannot be prevented above large mined-outareas in tabular salt deposits. The purpose of subsidence surveys has changed: such surveys at regular time intervals must show that surface subsidence occurs as soon as the prerequisites are fulfilled.

If and when surface subsidence cannot be detected at the time when it should become measurable, the safety of the mine workings may be in jeopardy. In such cases, the situation must be assessed very carefully. Potentially hazardous situations usually can be corrected by appropriate changes to mine development plans.

7.2 MEASUREMENTS OF SUBSIDENCE CONTROLLED BY PILLARS

7.2.1 Room-and-pillar mines

7.2.1.1 Potash mines, South Harz district of Germany

Considering the fact that surface subsidence surveys became compulsory above potash mines at the beginning of this century, one would expect that subsidence data had been presented in publications over the following decades. This, however, was not the case; on the contrary, the results of such long-term subsidence surveys were treated in a very secretive manner.

The reason may have been that the subsidence surveys showed surface subsidence which should not have occurred according to accepted hypotheses. However, the more subsidence data accumulated, the more apparent became the fact that surface subsidence cannot be prevented when tabular salt or potash beds are extracted using the room-and-pillar method.

At the beginning of the 1950's, the public discussion of surface subsidence data accumulated in the South Harz potash mining district was triggered by several serious accidents in a number of potash mines; the published controversies centered on the que-tion of whether or not overburden subsidence must be prevented according to the postulate of structural stability for salt and potash mines.

The opposite view was that overburden subsidence must be allowed, and initiated by appropriate mine development, in order to prevent floor deformations which had been recognized as the cause of gas discharge from reservoirs below the mine workings.

The surface subsidence data shown in Figs. 7-3 and 7-4 played an important role in the controversial discussions. For this reason, the data are presented in some detail. As a matter of fact, this writer urged RUHMANNSEDER (1955) to publish the data.

The potash mine referred to is the Bleicherode potash mine located approximately in the center of the South Harz potash mining district of East Germany (GDR). The measurements commenced on 20 observation points in 1908, shortly after two shafts had been sunk. Additional points were installed corresponding to the mine development to cover the extracted area. In 1950, 260 observation points were surveyed at regular time intervals.

Precise levels were taken at time intervals of 2 to 5 years, and evaluated by RUHMANNSEDER (1955) as shown in Figs. 7-3 and 7-4. The figures also show the mine development as dictated by geological conditions: as only sylvinite was mined at least until 1955, the mine extended to the W of the two shafts, see Fig. 7-3 with the 1939 boundaries of the mined-out area. Exploration for extractable sylvinite to the N, E, and S of this area had only limited success as shown by the 1950 boundaries, Fig. 7-4. For more geological details the reader is referred to BAAR (1952a) and to more recent publications summarized by STOLLE (in

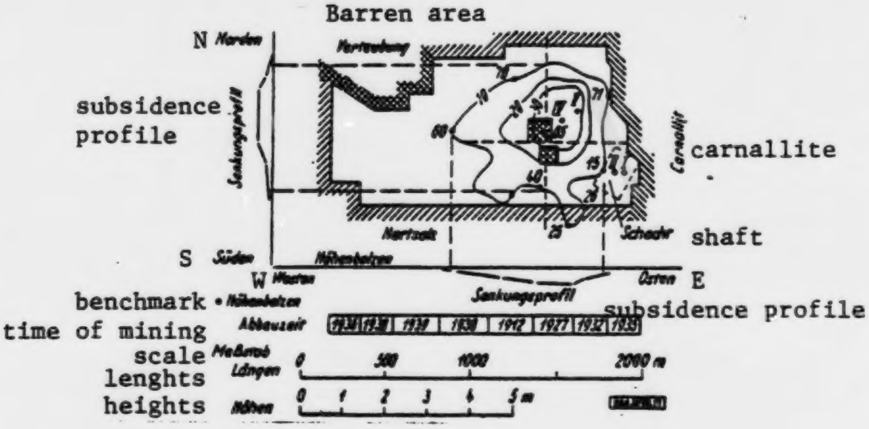


Fig. 7 - 2: Bleicherode potash mine
Subsidence until 1939 (RUHMANNSEDER, 1955)

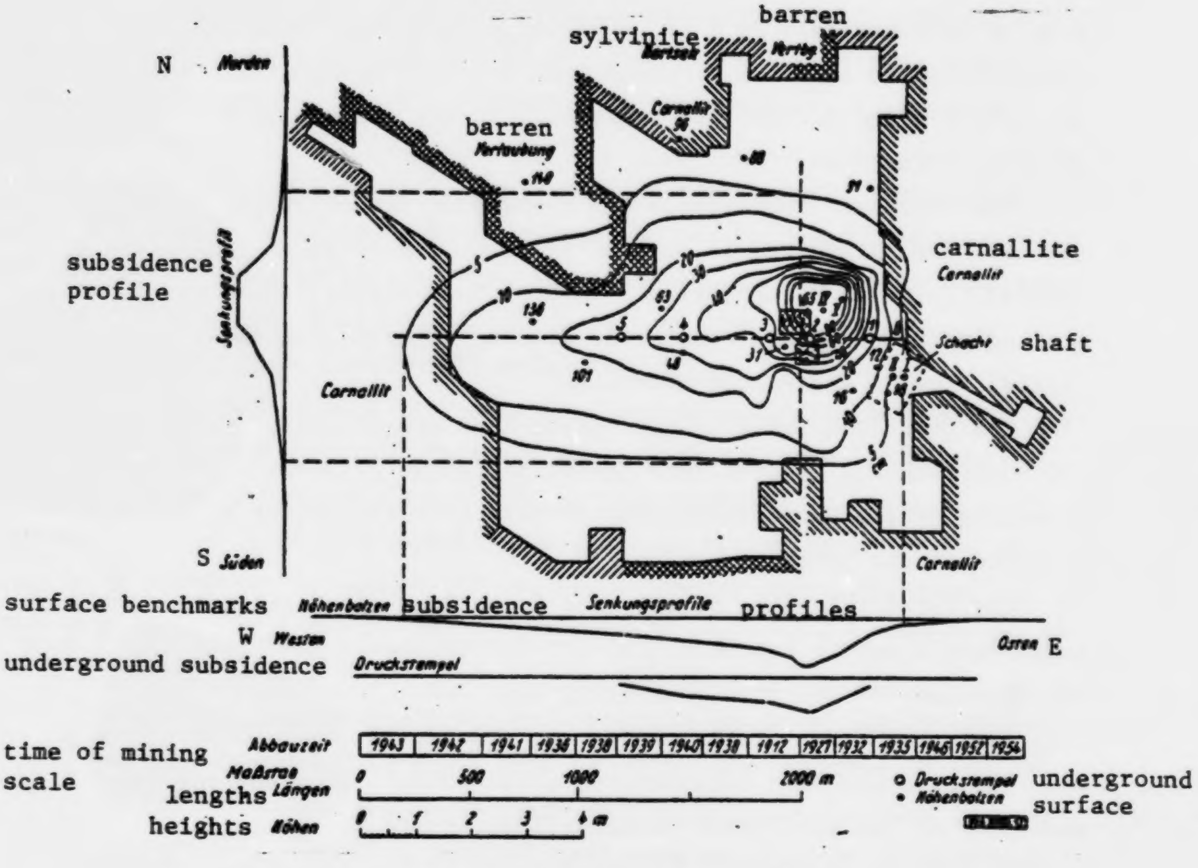


Fig. 7 - 4: Bleicherode potash mine

Subsidence until 1950 (RUHMANNSEDER, 1955)

GIMM, 1968, Figs. 2/17 and 2/19).

The potash bed mined in the Bleicherode mine is the Stassfurt potash bed which was altered locally as shown in Figs. I/2-16, I/2-19, and I/2-20, which are reproducted on the following page. These figures also indicate the thicknesses of the strata of interest with regard to the rock-mechanical effects of potash extraction: the Stassfurt potash bed is underlain by approximately 50 m of rocksalt; provided the impermeability of this protective salt bed is conserved, the mine workings are safe against gas and/or brine inflow from reservoirs in the underlying anhydrite and dolomite formations.

The immediate roof strata are made up of the following normal sequence: the potash bed is covered by 15 - 20 m of saliferous clay (shale), followed by approximately 40 m of anhydrite; these two formations are badly fractured and completely missing at some locations, see BAAR (1965a, Figs. 6 and 7) for examples.

The fractured shale and anhydrite beds are followed by approximately 100 m of rocksalt grading into anhydritic shale. The main overburden formation is the Bunter Sandstone covered by a few metres of alluvial deposits at the present surface.

The total thickness of the roof formations is approximately 600 m, increasing slightly to the S, but decreasing sharply to about 450 m near the NE corner of the mined-out area, Fig. 7-4.

Indications of solutioning of the 100-m-salt cover above the mine workings have not been detected; in other words: provided the impermeability of the salt cover is maintained, there is sufficient protection against the groundwater in the upper parts of the sandstone formation. As the sandstone formation also appears to have suffered fragmentation, the possibility of groundwater access to the top of the salt formation must be considered. However, solutioning apparently did not occur above the mined-out areas as related surface features are missing.

The extracted anhydritic sylvinite is generally well-stratified; the average mineralogical composition of the extracted ore delivered to the refinery was (RUHMANNSEDER, 1955): kainite 50%, sylvite 23%, anhydrite 19%, carnallite 6%, kieserite 1%, clay 1%.

As the anhydrite sylvinite is concentrated in layers up to 20 cm thick, such layers may provide additional resistance against pillar transverse expansion by creep.

According to RUHMANNSEDER (1955, p. 88), the pillar dimensions were: length 150m, width 8 - 10m, height 3 - 15m, depending on the thickness of the sylvinite seam. The rooms were 12m wide. Carnallite, although not mined at least until 1955, was exposed in numerous mine workings, particularly in travelways and exploration headings.

The pillar widths chosen at this mine were very conservative in comparison with those of only 5 - 6m at other mines in the same district, presumably because of the bad experience of the operator at Stassfurt, see 2.2.

Starting as early as 1912, the mined-out rooms at the Bleicherode mine were backfilled with refinery waste. It was believed, and some still believe that such backfill improves considerably the supporting capacity of mine pillars and makes the pillars stable so that the mine can be designed according to civil engineering principles.

This, of course, is a very dangerous misconception because it disregards the fact that the refinery waste is hot (about 100°C) when leaving the refinery) and causes considerable temperature increase of the rock around backfilled rooms. The elevated temperatures result in increased plasticity of saltrocks and corresponding increased creep deformations. For details, the reader is referred to I/3.7, specifically to Figs. I/3-9 and I/3-10.

Furthermore, the refinery waste is transported in pipelines using large amounts of brine; operators tend to overdo the watering of the pipelines for cleaning. Quite frequently, particularly in areas used as underground brine reservoirs, mine pillars were undercut by solutioning, see Chapter 5 for details and case histories.

Disregard of these important relationships caused serious difficulties in the western part of the South Harz district where the salt sequence underneath the potash bed frequently is less than 60m thick, depending on the topography of the underlying anhydrite/dolomite formations. These formations contain gases and/or brines in suitable geological structures; when such gases are released unexpectedly into the mine workings because of excessive floor deformation, disastrous explosions may occur, see 3.5.

RUHMANNSEDER (1955) emphasizes the fact that the Bleicherode potash mine experienced gas discharges from the floor in spite of the exceptional pillar width and of normal salt thicknesses of 50 - 60m between the floor of extracted rooms and the top of the gasbearing anhydrite/dolomite formation.

Such gas discharges became particularly serious in 1944 as they resulted in several explosions with numerous fatalities. For several subsequent years, the gas content of the exhaust air remained measurable at the surface. Under a compulsory agreement with the German National Research Council, this writer was assigned to investigate the origin of the gases and the causes of their unexpected release. Needless to say that, at that time, the results of this investigation were classified ("confidental"). However, they were remarkable in several aspects and showed particularly that the subsidence characteristics of Fig. 7 - 1 must be considered carefully in developing potash mines in that mining district.

Some results, and conclusions are presented with reference to Figs. 7-3 and 7-4.

1. Gas discharge occurred in the narrow extension of the mined-out area to the NW outside the 5-cm (1950) surface subsidence contour line of Fig. 7-4. The span of this area was about 300m. At the time of the peak gas discharge in 1944, hydraulic backfilling was in progress. There was no indication of pillar failure; spalling off the pillar surfaces apparently was caused by stress relief creep. At some locations, leaching of carnallite layers had caused additional weakening of such pillars.
2. No surface subsidence was detectable. Apparently, the main overburden load was transferred by bridging overburden formations to the virgin ground at the NE and the SW flanks of the extracted area. This had to be expected because of the relatively small span of the mined-out area.
3. The whole mined-out area was filled with gases in concentrations far above the explosion limits of methane. Several methane explosions were set off in access entries; lack of oxygen resulted in high CO-contents of the gases in the mined-out panel. Gas samples were taken in open rooms where gas bubbles were found rising in brine puddles. These original gases, apparently escaping from floor strata consisted mainly of CH_4, but did not contain any CO.
4. It was necessary to flush the extremely poisonous gases out of the

mined-out area over an extended period of time in order to make sure that sufficient dilution in fresh air was achieved before the gases reached mine openings which had to be entered by mining crews.

5. There was strong evidence that similar gas discharges and explosions in other potash mines of the same district - some were in use for military purposes - had been caused by the same mechanism. It goes without saying that casualty figures had to be kept secret and are not included in statistics published later, e.g., GIMM (1968).

However, published discussions and controversies regarding the supporting capacity of potash mine pillars should be considered with such disasters in mind. As this writer put it (BAAR 1971a, Vol. 1: 39/40):

"Indeed, one does not look favorably upon academic disputes regarding pillar stability while searching for the source of gases which have filled all rooms in a potash panel with pillars showing no indication of failure. The gases, however, bubbled up through brine puddles on the floor, and left no doubt as to their origin from reservoirs below the salt. So the sealing salt formation must have been damaged by excess deformation in spite of pillars which are certified as stable. This experience in 1944 was this writer's first, but lasting disillusionment with theories on pillar stability in potash mines, after several people had been killed".

Fig. 7-3 clearly shows: in 1939, overburden subsidence was measurable only near the center of the mined-out area. The subsidence profiles show the characteristics of Fig. 7-1. However, no surface subsidence occurred in the western part of the mine, apparently because the necessary spans of mined-out areas had not yet been reached.

One conclusion appears unescapable: under the given geological conditions, effective overburden subsidence must be initiated in order to ensure sufficient pillar loads at all times to control potentially dangerous floor deformations.

On the other hand, Figs. 7-3 and 7-4 also show conclusively that controlled overburden subsidence does not jeopardize the impermeability of the salt cover.

Considerable surface subsidences were recorded near the center of the developing subsidence trough where approximately 12 pillars had been mined from 1920 to 1930.

The rooms adjacent to the extracted pillars had been backfilled carefully with refinery waste. In 1939, see Fig. 7-3, this secondary pillar mining (total extraction) had resulted in a surface subsidence trough with the maximum depth of 39cm. No detrimental effects such as gas discharge from the floor of the totally extracted area or water seepage from the roof could be detected.

Convergence measurements in a travelway through the totally extracted area indicated virtually constant convergence rates. At the measuring sites 4 and 5, see Fig. 7-4, the convergence accelerated when the extraction front progressed to the S and to the W, resembling the development shown in Figs. I/5-2, I/5-16, and I/5-19.

The development of the convergence rates at sites 4 and 5 indicated full pillar reloading according to depth and extraction ratio; the subsidence over most of the extracted area was controlled by creep deformation of the pillars, and the underlying salt strata.

The 1950 surface subsidence profiles and contour lines, Fig. 7-4, clearly demonstrate the subsidence characteristics of Fig. 7-1, with the exception of areas where the necessary spans had not yet been reached; the latter applied particularly to the southern part of the extracted area with large remnant pillars (not shown in Fig. 7-3). It is emphasized that the measured surface subsidence trough was extending considerably beyond extraction fronts which had been stationary for several years, exactly as would be expected from Fig. 7-1.

The favorable development of overburden subsidences and the lack of extractable ore at the 1950 boundaries of the mine encouraged the initiation of another phase of secondary pillar mining. An area including the convergence sites 4 and 5, Fig. 7-4, was chosen; the surface subsidence contours indicated overburden subsidence controlled by creep deformations underground. In order to maintain effective control of the overburden, only every second pillar was extracted in the first phase, and the resulting openings were immediately backfilled with refinery waste. For details, the reader is referred to RUHMANNSEDER (1950) and numerous other publications, e.g., JUNGHANS and ECHTERMEYER (1953), GIMM (1968, with references to earlier publications).

At that time controlled overburden subsidence above room-and-pillar potash mines was not yet acceptable to the top experts at the Freiberg

Mining Academy although the surface subsidence measurements reported by RUHMANNSEDER (1955, see Table 7-I for some data) showed no difference in the development of subsidences above and outside the area of secondary pillar mining. When the extraction of every second pillar began, precise levelling of the surface had to be done in intervals of three months; the subsidence data clearly indicated that the settlement of the overburden was safely controlled by the remaining pillars (BAAR, 1953a; RUHMANNSEDER, 1955).

Nevertheless, in 1953 the secondary pillar mining was halted because of the above-mentioned objections which were published by JUNGHANS and ECHTERMEYER (1953); an advisory committee chaired by GIMM ruled that overburden subsidence should not be allowed in that mining district. The main purpose of RUHMANNSEDER's (1955) publication was to support the opposite view (BAAR, 1952b - 1954d) that surface subsidence must be initiated, and should not be disturbed by so-called barrier pillars postulated by the SPACKELER/GIMM school (e.g., SPACKELER, 1956; HÖFER, 1958a, numerous other publications).

These controversial issues were again discussed in 1958 on occasion of two international conferences in Berlin and Leipzig (BAAR, 1958, 1959b; WILKENING, 1959). At that time, the hypotheses held by the SPACKELER/GIMM school appeared unchanged. The barrier-pillar concept for the prevention of any overburden subsidence was still promoted by GIMM and PFORR (1961).

In view of these publications, Fig. 7-5 appears rather strange: according to GIMM and SIEGMUNDT (1975), GIMM (1959) discovered that controlled overburden subsidence should be accepted in salt and/or potash mining.

It is emphasized that mining methods with controlled overburden subsidence have been practiced for many decades in other potash mining areas, e.g., Alsace (France) and New Mexico (U.S.A.), without any significant problems. However, the SPACKELER/GIMM school raised objections to controlled overburden subsidence resulting from secondary pillar mining at the Bleicherode potash mine, and achieved a temporary stop (JUNGHANS and ECHTERMEYER, 1953, p. 23). Ironically overburden subsidence had to be initiated in this particular case to prevent dangerous floor deformations, as outlined above.

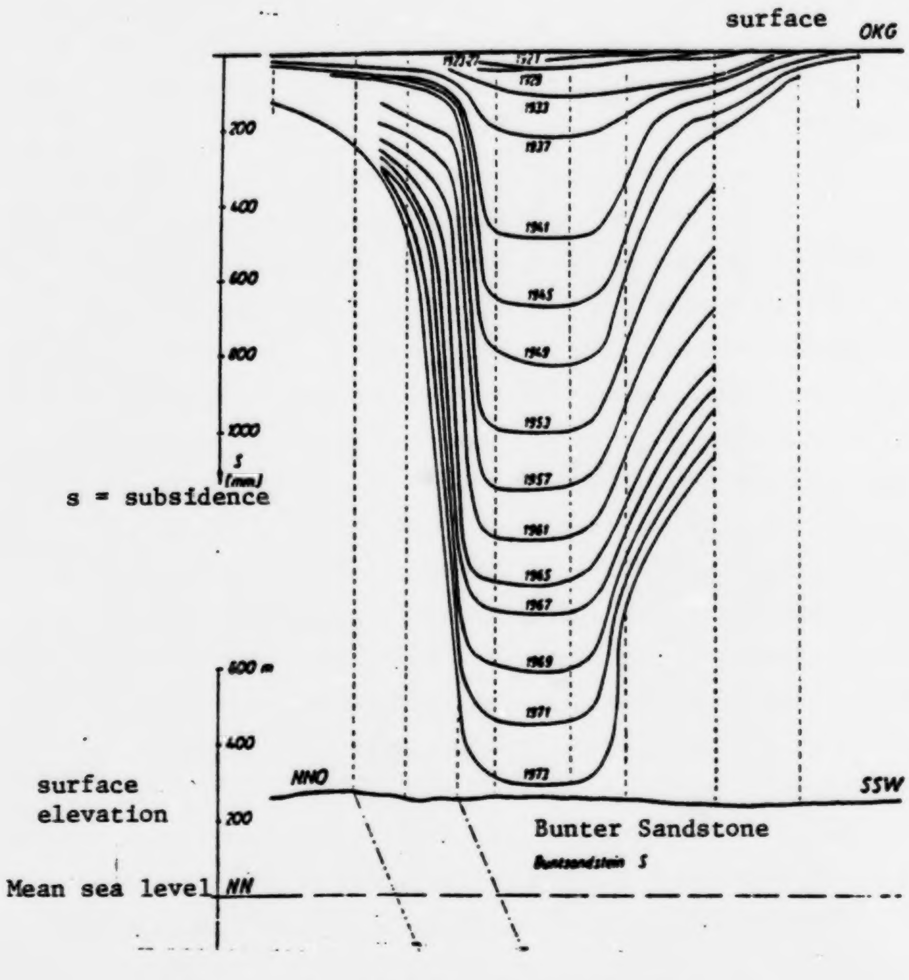


Fig. 7 - 5: Bleicherode potash mine
Subsidence 1923-1973 (GIMM and SIEGMUNDT, 1975)

TABLE 7 - I

Surface subsidence, Bleicherode potash mine, 1950-1954 (after RUHMANNSEDER, 1955)

Measured subsidences in mm; note: the first column ('50-'52) refers to a two-year period A = points above area of secondary pillar mining, B = points outside area A.

No.	'50-'52	'52-'53	'53-'54	Total '50-'54	Remarks
A 64	8	8	8	24	
A 48	9	6	7	22	
A 265	4	4	7	15	Near borehole pillar
A 201	4	5	6	15	Near remnant pillar
A 264	3	5	7	14	Near remnant pillar
A 63	8	8	7	23	
B 45a	9	5	7	21	
B 49	10	6	6	22	
B 55	8	8	6	22	
B 134	2	4	5	11	Near remnant pillar
B 62a	4	8	6	18	Near remnant pillar
B 57	12	6	7	25	

As other theoreticians continue to promote hypotheses which promise structural stability of salt and potash mines even at great depths, the publication of Fig. 7-5 by GIMM and SIEGMUNDT (1975) is very much appreciated.

Regrettably, the writers provide no information to explain the acceleration of the surface subsidence near the SSW end of the profile from 1949 to 1965. For the following years until 1973, the subsidence above this area is shown as slightly decelerating, while the subsidence above the central area of the mine is accelerating considerably. It should be noticed that the profiles after 1965 indicate subsidence for 2-year periods, while 4-year periods are shown for the preceding 2 decades.

The accelerated subsidence above the central area of the mine appears to be indicative of extensive secondary pillar extraction. The following figures of maximum surface subsidences during different extraction periods can be calculated from Fig. 7-5: the first metre of maximum surface subsidence was measured in 1953; approximately 0.9m took place since 1933 at an average rate of 45mm/year. The second metre occurred from 1953 to 1973, i.e., at an average rate of 50mm/year. Since 1967, the average maximum subsidence rate was 76mm/year; there is no indication of any decrease in these considerable rates.

The acceptance of overburden subsidence rates of such magnitudes is remarkable indeed; it confirms the complete change of theories now being applied to the design of potash mining operations in the South Harz district. However, serious questions arise as to the pillar dimensioning techniques promoted in previous publications, e.g., GIMM (1968) and numerous other publications, which refer either to DREYER (since 1955), HÖFER (since 1958), or to newly developed techniques, e.g., GEORGI et al. (1975). GIMM and SIEGMUNDT (1975) no longer mention these techniques which were supposed to ensure structural stability of salt and potash mines on the basis of laboratory data. This may indicate that the misleading techniques were finally dropped in view of the overwhelming evidence provided by long-term surface subsidence measurements.

Figs. 7-6 and 7-7 (HÖFER, 1958) are shown as other examples of measured long-term surface subsidence after room-and-pillar mining of the Stassfurt potash bed in the same mining district. Mining depths and geological conditions are about the same as in the case history dealt with in the foregoing, except for the protecting salt sequence below mined-out areas which is approximately 80m thick and practically eliminates the potential of gas and/or water discharge from reservoirs underneath the mine.

The mining sequences are not indicated in the reference publication, so it is not possible to interpret adequately the surface subsidence profiles which developed over time periods exceeding 25 years. However, it is most instructive to compare HÖFER's (1958) and GIMM's (1959) ideas with the revised hypotheses presented by GIMM and SIEGMUNDT (1975). The mine referred to is the Sondershausen potash mine with designed room width of 10m and pillar width of 5m. However, HÖFER (1958, p. 48) emphasizes that some pillars were only 2 - 3m wide after spalling off both pillar sides. Pillar heights for the extracted panels referred to are not given, but may have exceeded 5m.

Figure 7-7 is presented as an example of what is called the "normal" development of surface subsidences over the indicated period of time

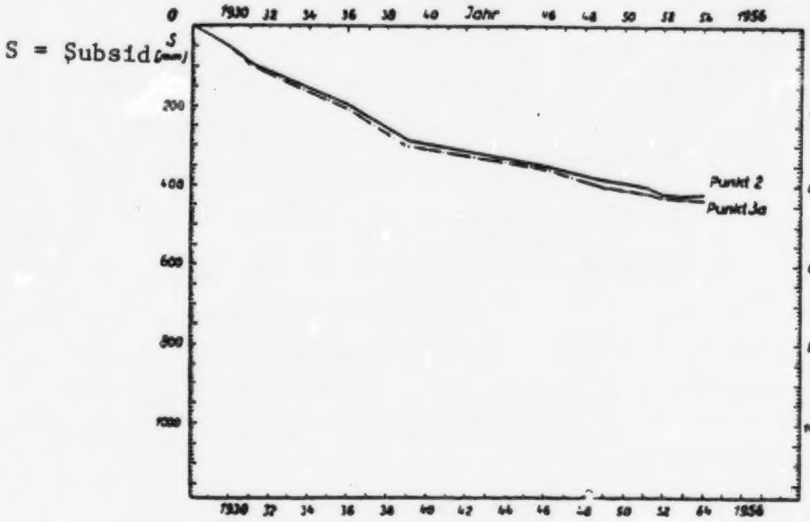
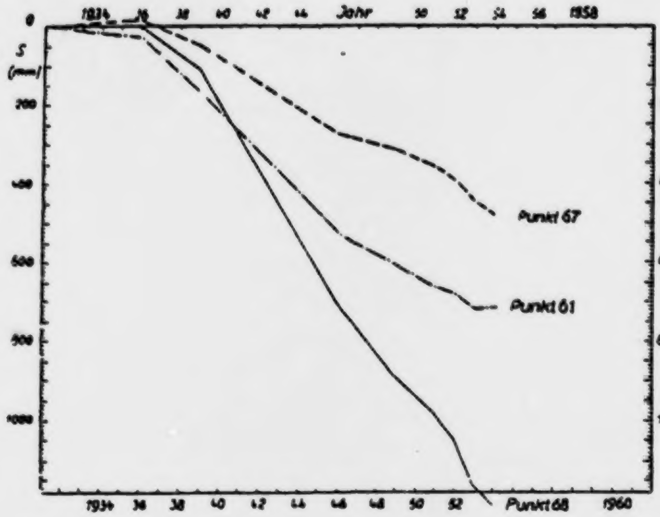


Fig. 7 - 6: Sondershausen potash mine
Surface subsidence 1928-1954 (HÖFER, 1958a)



S = subsidence

Fig. 7 - 7: Sondershausen potash mine

Surface subsidence (HÖFER, 1958a)

1932-1954

(1928-1954). The term "normal" refers to the time of backfilling after extraction; immediate backfilling of extracted panels with refinery waste is called "normal". The reader is reminded of the obsolete expectation that immediate backfilling was to improve the supporting capacity of pillars so that the overburden would remain in its original position, i.e., no significant surface subsidence would take place.

Figure 7-6 clearly demonstrates the opposite: during the first three years, the highest subsidence rates of approximately 300mm/year were recorded, indicating the negative effect of the temperature increase caused by hot refinery waste. The subsidence curves also indicate that the extracted panel was located within a large mined-out area over which subsidence was already in progress.

For the last 15 years Fig. 7-6 shows virtually constant subsidence rates of approximately 10mm/year, indicating continuing creep at constant rates in and around the extracted panel.

HÖFER (1958, p. 50) considered average surface subsidence rates of 16mm/year as calculated for the total 26-year period as "admissible", although according to theory, the overburden was to be kept in its original position.

Similar surface subsidence rates had been measured above other potash mines in the South Harz district, see Table 7-II. However, BAAR (1959b, p. 53) warned against such interpretations as most extracted areas do not reach the spans required for unrestricted overburden subsidence; Figs. 7-3 through 7-5 demonstrate effects of bridging overburden formations: surface subsidences became measurable only after sufficient spans of mined-out areas had been reached, confirming the subsidence characteristics outlined in section 7.1.

Fig. 7-7 (HÖFER, 1958, Fig. 24a) shows similar relationships: until 1936, the surface subsidence was minimal, apparently because the span of the mined-out area was too small. The measuring points 61 and 67 were located above the boundaries of an extracted area with the span of 250m; point 68 was located above the center. Regrettably, the writer fails to provide exact data on the mining sequence in and around the mined-out area referred to. Apparently, the area was backfilled begining in 1952, as indicated by accelerated subsidences of all three measuring points. The effect of the temperature increase is particularly

TABLE 7 - II

Average surface subsidence rates, room-and-pillar potash mines, South Harz district

Note: subsidence rates measured above mined-out areas with spans smaller than depths

Mine location	Average depth of extraction (m)	Average surface subsidence rate (mm/year)
Rossleben	450	8 - 10
Bleicherode	600	10
Bischofferode	600	10
Sondershausen	675	16
Volkenroda	1,000	15

evident at point 68 which showed the highest subsidence rate of 87mm/year in 1952 (HÖFER, l.c., p. 50). The average subsidence rate from 1931 to 1954, including the first years to 1936 with no measured subsidence, was 52mm/year at point 68.

Although the writer provides no data, the subsidence of the three reference points allows to reconstruct the mining sequence. The writer notes that the extracted area remained without backfill for 12 years.

At point 61, above the western boundary of the area referred to, surface subsidence became measurable in 1931, indicating that the area to the W of this point had already been extracted prior to the time period shown in Fig. 7-7. The next point to show subsidence - in 1936 - was the center point 68. Point 67, above the eastern boundary, followed a year later. This sequence clearly indicates that the extraction progressed from W to E.

From 1936 to 1946, the subsidence rates of points 61 and 67 were virtually constant at approximately 50mm/year and 30mm/year, respectively. The smaller rate above the eastern boundary (point 67) indicates that the extraction front became stationary near this point.

The subsidence of point 68 shows a different development: in 1939, the subsidence rate of approximately 40mm/year increased to 60mm/year;

no acceleration was recorded at the two other points, indicating that extraction outside the reference area affected point 68. The fact that point 61 showed no reaction may indicate extraction northeast or southeast of point 68.

The slight decreases in subsidence rates at all points after 1946 appear to indicate that extraction ceased around the area covered by the reference points.

It is emphasized that the surface subsidence rates shown in Fig.7-6 are much higher than those shown in Fig. 7-3, and particularly in Fig.7-4 from 1949 to 1953 for the area of secondary pillar extraction. As these data were known in 1953 - as a matter of fact, Figs. 7-6 and 7-7 show that considerable surface subsidences had been measured for 2 decades prior to 1953 - there was definitely no valid reason for shutting down the secondary pillar extraction at the Bleicherode potash mine in 1953 as discussed previously.

However, there was every reason for GIMM (1959) to realize earlier that overburden subsidence in that mining district must not be prevented regardless of whether or not the extracted rooms are backfilled with refinery waste. On the contrary, the acceleration of overburden subsidence by backfilling should also have been noticed.

Further evidence of the negative effects of using hot refinery waste for backfill is presented in Chapters 2 and 3.

It is not known if such effects influenced the development of overburden subsidence above another potash mine in the South Harz district shown in Fig. 7-8 (GIMM and SIEGMUNDT, 1975); the writers present this figure to show that surface subsidence cannot be prevented, even with the poor extraction ratio of 50% at relatively shallow depths - again demonstrating the complete change in hypotheses held until 1958.

Fig. 7-8 is presented here because it demonstrates how a typical rockburst situation was created by inadequate mine development. Apparently, the writers are not aware of these relationships; the hypotheses held by most writers, indlucing GIMM (1968), postulate that sudden failure of carnallite pillars causes the heavy rockbursts which are haunting the German potash mining industry, see Chapter 2.

GIMM and SIEGMUNDT (1975) give no details of room and pillar dimensions, times of backfilling, etc.; the data included in Fig. 7-8

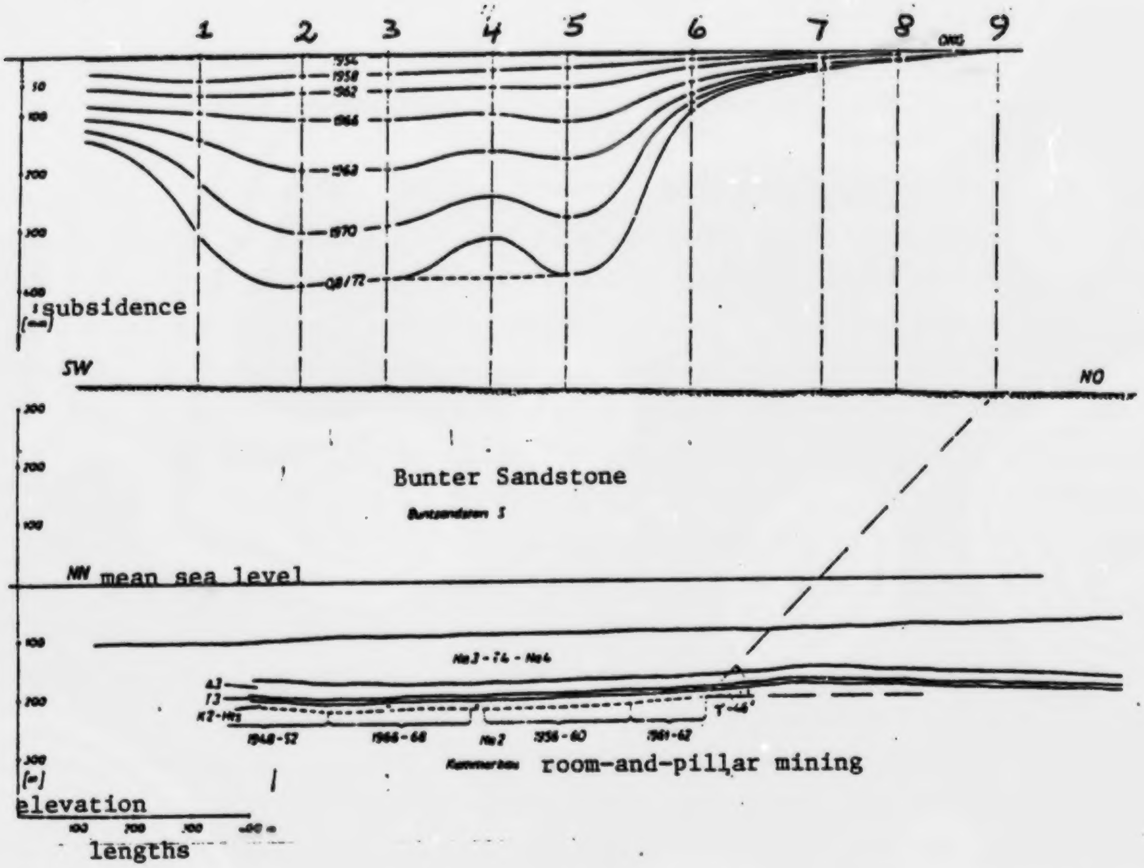


Fig. 7 - 8: Subsidence development, South Harz potash mine (GIMM and SIEGMUNDT, 1975)

Na 3-T4-Na 4 = younger salt sequence
A 3 = Main Anhydrite
T 3 = gray saliferous clay (shale)
K 2 - Hts = Stassfurt potash bed, sylvinitic
= 90° - angle of draw

show three periods of extraction of the Stassfurt potash bed at the depth of approximately 500m, slightly less than the mining depths for Figs. 7-3 through 7-7. It appears safe to assume that the usual pillar and room widths of 5m and 10m, respectively, were used as in the mine to which Figs. 7-6 and 7-7 apply. However, the writers refer to an extraction ratio of approximately 50%, and to extraction methods using competent pillars; this appears to indicate that the barrier pillar concept was applied, leaving a wider barrier pillars after a number of 5-m pillars.

The application of the barrier pillar concept became compulsory in that mining district during the early 1950's, and this resulted in published controversies (BAAR, 1954a, p. 139; 1959a, b). It appears that the barrier pillar concept was dropped in the mine referred to during the second extraction period (1956-1962); this is indicated by the subsidence profiles shown in Fig. 7-8.

It should be noticed that the surface subsidence profiles of Fig.7-8 refer to 4-year periods until 1966, and to 2-year periods thereafter. As the time of the first levelling is not indicated, the question of whether or not surface subsidence occurred prior to 1954 remains open.

An area of unknown extent to the SW of point 1 was extracted before or during the first extraction period (1948-52) referred to; the subsidence rate at the SW end of the profile is shown as virtually constant at approximately 7mm/year. Subsidence at the same rate may have occurred prior to 1954.

The 1958 profile shows point 1 in the center of a local subsidence trough with the maximum depth of 50mm; the subsidence rate of point 1 calculates as 12.5mm/year.

The 1966 profile shows the local subsidence trough considerably wider, with the maximum subsidence shifted to points 2, 3, and 5. Point 3, located above a 300-m wide remnant pillar which was not mined prior to 1966, showed the highest subsidence rate of 15mm/year from 1962 to 1966. As the accelerated subsidence of points 2 and 3 cannot be related to extraction during the first extraction period which terminated in 1952, it may be concluded that it was caused by backfilling the extracted area underneath points 1 and 2 with hot refinery waste, similar to what is shown by Fig. 7-7.

Point 1 participated in the acceleration after 1966. However, the maximum subsidence shifted back to point 2, with rates of 40mm/year from 1966 to 1968, and 50mm/year from 1968 to 1970. As the 300-m remnant pillar was extracted from 1966 to 1968, the acceleration in surface subsidences is in part attributable to extraction; however, the effects on points 1 and 2 appear to indicate that the backfilling with hot waste was the main factor.

The writers fail to give the reason why the extraction was halted near point 2 in 1952, and resumed at point 4 in 1956. The 300-m remnant pillar left between the two extracted areas resulted in the development of a separate subsidence trough, with point 5 showing the maximum subsidence near the center of the separate trough.

The extraction resumed in 1956, and resulted in 25mm subsidence until 1958, i.e., the subsidence rate during this time period for point 5 was the same as for point 1. The immediate reaction of the overburden is remarkable, clearly indicating stress-relief creep in the newly extracted area.

The effect of the barrier pillar is evident in the 1966 profile: points 2 and 5 show an equal amount of maximum subsidence since 1954, while point 4 above the edge of the barrier pillar shows less subsidence.

The separate subsidence trough around point 5 became more accentuated after 1968, apparently because the extracted area was backfilled with hot waste. It should be noticed that the assumed backfilling resulted in more surface subsidence than did the extraction of the barrier pillar: the hump above the barrier pillar underneath point 4 became higher after the extraction had been terminated in 1968. It appears that the barrier pillar could not be extracted as planned because of overlapping high abutment loads from overburden bridging across the two adjacent mined-out areas.

The surface subsidences measured between points 6 to 9 show the width of approximately 400m of the abutment zone at the NE end of the profiles. According to Fig. 7-1, the width of tension zones above the boundary of large extracted areas can be assumed as slightly greater than the width of the abutment zones. This means that at least two tension zones were overlapping above the barrier pillar underneath point 4, the tensional forces acting in two opposite directions. This is one typical rockburst situation, see Chapter 2.

It may be re-emphasized that other prerequites must also be fulfilled to cause an actual rockburst due to sudden tensile failure of overburden formations. Immediate surface subsidence after extraction and immediate reaction to temperature increase caused by hot backfill indicate that no excess tensile stresses are building up. For these reasons there was no danger of severe rockbursts in all case histories shown in Figs. 7-3 to 7-8.

It is re-emphasized that the potash mines in the South Harz district are protected by a cover of 100m of rocksalt, unless the extraction comes too close to areas which are affected by salt solutioning due to groundwater action. When effective overburden subsidence has been initiated, and is controlled by pillars with sufficient supporting capacity, the stress field in the salt cover remains nearly hydrostatic with the local stresses increasing with increasing distances from mine openings.

In other words: the salt cover remains under triaxial compressive stress conditions. Tensile stresses may develop in non-salt formations, but the salt cover accomplishes necessary deformations by creep which maintains the impermeability.

This mechanism is accountable for the fact that groundwater leakage into the potash mines of the South Harz district does not occur, provided the extraction does not enter into solutioned areas.

Until the early 1950's when the controversies referred to above resulted in numerous publications, surface subsidence troughs with depths of several metres had already developed above some mines - however, at that time, no data was available for publication. For this reason, the publication of subsidence data by GIMM and SIEGMUNDT (1975) is again acknowledged; the data clearly demonstrate why earlier hypotheses of stability had to be abandoned.

7.2.1.2 Werra potash mining district, Germany

The Werra basin of Central Germany is relatively small; two potash beds were deposited during the Zechstein 1 cycle of evaporite deposition. The subsequent cycles did not produce any noteworthy salt deposits. However, the main overburden formation is the same as throughout the Zechstein basin of northern Europe: a sandstone formation up to approximately 500m thick, unless partially removed by erosion.

Salt solutioning occurred along the edge of the basin, and at numerous isolated locations throughout the basin. Tectonic events associated with volcanism severely affected the salt and potash deposits, see I/2.4.3, particularly Fig. I/2-21. Although such events also affected the overburden formations, this district has become known for the largest rockbursts caused by potash mining; details are presented in Chapter 2.

Potash mining started at the beginning of this century, concentrating first on mining the upper potash bed under a salt cover of about 100m at locations not affected by salt solutioning. Some of the older mines soon ran into difficulties when coming to close to solution areas; in general, the resulting brine inflows could be mastered by sealing the respective exploration drifts. Some of the mines at shallow depths of around 300 - 400m were abandoned, but re-opened during the 1930's to serve military purposes. Limited secondary pillar mining was done during the 1960's, see 7.3.2.2 for related surface subsidence measurements.

During the earlier mining at relatively shallow depths, the chosen pillar dimensions definitely were on the safe side, probably due to experience in the Stassfurt area. The pillar widths were 10 - 12m, the extracted seams were only 2 - 3m thick. Long rooms up to 250m in length and 20m wide were extracted - provided that the potash bed was encountered in adequate quality. Frequently, the ore composition was considered inadequate for various reasons; such areas were left unextracted, and this practice resulted in numerous remnant pillars throughout mined-out areas. In general, the spans of mined-out areas required to initiate measurable overburden subsidence were not obtained during the first decades of potash mining in the Werra district.

This experience may have contributed to the erroneous belief that the chosen design parameters were adequate to prevent any surface subsidence even when mining progressed to greater depths up to 1000m, and when carnallite was mined. Such belief was promoted particularly by HÖFER (1958); it is still promoted in recent East German publications. For this reason, the following results of surface subsidence measurements above the Hattorf potash mine (UHLENBECKER, 1968, 1971) are presented here.

Related underground subsidence measurements are dealt with in I/5.2.5, see particularly Fig. I/5-7 which also shows the 1974 extent of the mined-out area of the upper potash bed. Extraction of the lower potash bed apparently began around 1970 in direction to the south of the twin mine shafts indicated on the figure; the underground subsidence trough shown at the distance of about 1km to the S apparently resulted from extraction of the lower potash bed. This becomes apparent from a mine map published by SCHNEIDER (1973). The writer reveals considerable changes to the design dimensions of rooms and pillars never mentioned by UHLENBECKER (1974), confirming that this writer's (BAAR, 1971b, 1972a) criticism of the design principles promoted after HÖFER (1958) was necessary, see 3.1.

In contrast to the practice adopted in other German potash mining districts, the mined-out rooms in the Werra district are not backfilled with refinery waste. This is not because of rock mechanical considerations, but mainly because of the lack of refinery waste: after the extraction of the potash values from the ore, the $MgSO_4$ is extracted by selective dissolution of the rocksalt. This process yields huge amounts of brines the disposal of which causes serious problems. The brines are injected into a porous dolomite formation above the salt sequence, replacing the original content of the pore space. For details, the reader is referred to FINKENWIRTH (1967), see 2.3.5.

Surface subsidence measurements above the Hattorf mine were initiated in 1954, shortly after the first devastating rockburst in the Werra district occurred above the adjacent Wintershall mine, see 2.3 for details. This event came as a shock to many theoreticians who had declared this mining district as absolutely safe against rockbursts above potash mines. Figure 7-9 (UHLENBECKER, 1968 - 1978) shows the surface subsidence profile that developed from 1954 to 1967 along a W - E section just south of the mine shafts. Many more profiles and contour maps which show the development over time periods of 3 - 4 years can be found in the writer's 1968 publication. The writer emphasizes that his findings confirm observations in coal mining districts, i.e., the validity of Fig. 7-1 with the exceptions mentioned previously: the limiting value of surface subsidence cannot be expected in many decades;

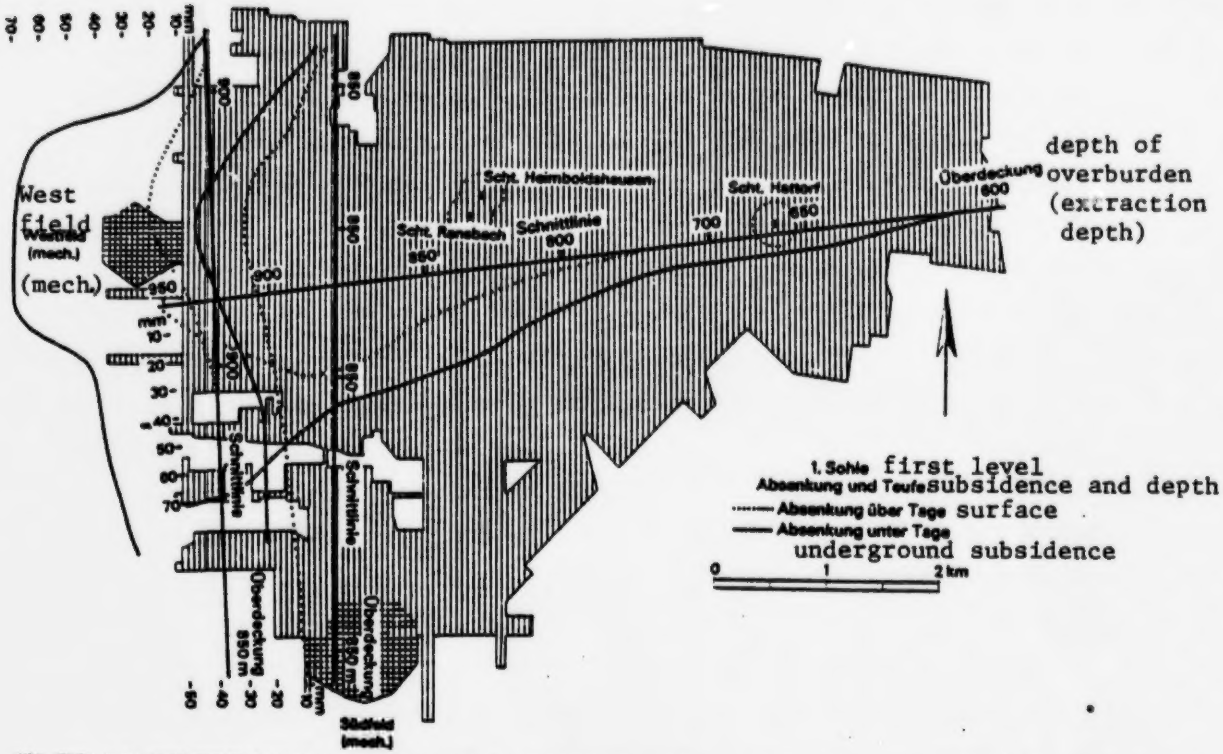


Fig. 7 - 9: Hattorf potash mine, Werra district
Surface and underground subsidence (UHLENBECKER, 1968-1978)

Schnittlinie = section line
Scht. = shaft

the underground convergences continue to take place at virtually constant rates; after initial stress relief creep, which, of course, was not recognized by the writer who continues to believe in misleading laboratory testing. UHLENBECKER (1968, 1971) refers specifically to underground convergences measured over a 30-year period since 1932; the selected data appear to indicate decreasing convergence rates according to the hypotheses promoted by the writer. In some contrast, Figure 7-9 shows no measured surface subsidences at all for the eastern part of the profile, although the underground convergences continued. It appears obvious that surface subsidence above a large mined-out area cannot terminate if underground convergence continues unless there are other reasons why no surface subsidence occurs.

One possible reason may be related to the subsurface disposal of brines into the dolomite formation above the extracted area. On the other hand, the published mine maps show relatively large remnant pillars left below the eastern part of the subsidence profile.

Any further discussion of such possibilities on the basis of the data published by UHLENBECKER would be merely speculative. The published data were arbitrarily selected to prove preconceived hypotheses. The remarkable discrepancy between selected surface subsidence data and selected underground convergence data shows again the need for careful evaluation of some publications, particularly when they appear again and again without any reference to published criticism.

UHLENBECKER apparently intends to show similarities between room-and-pillar mining of potash beds, with the extraction front advancing approximately 30m per month, and longwall mining of coal seams; he claims that his measurements show full pillar loads according to depth and extraction ratio at distances of 100 - 150 m from the advancing extraction front. This postulate is questioned in 3.1. It may be added here that Figure 7-9 definitely disproves such hypotheses for the following reasons:

At the western end of the W - E profile, beginning at the distance of about 1000m from the western boundary of the mined-out area, the two convergence curves diverge more and more from each other. The surface subsidence profile shows the maximum subsidence of 30mm at about 1000m distance from the extraction front; it reaches the value of about 10mm above the boundary of the mined-out area. In some contrast to the subsidence troughs shown so far in this text, the surface subsidence ends rather abruptly about 200m outside the mined-out area. The reliability of the data is not questioned, particularly in view of the N - S strike of the major geological disturbances in the area, see 1.2.1.

The underground subsidences reach the maximum value of 70mm at the extraction front. Considering the depth of nearly 950m, there can be no question as to the causes of the apparent underground subsidence near the boundary of the mined-out area: these measured subsidences are clearly caused by stress-relief creep as shown in detail in I/4 and I/5.

The width of 1000m of a zone along an advancing mining front at depths over 900m within which the pillars are not yet fully reloaded should not be considered unlikely; several rockbursts in the Werra district have demonstrated near-elastic behavior of the main overburden formation. The relationships between overburden behavior and stress-relief creep in mined-out areas are dealt with in detail in Chapter 2.

It remains to be seen how the change-over to standard room-and-pillar design in 1957 affected the long-term development of surface subsidences. The effects should have become measurable. However, frequently when writers publish premature claims of successful application of new design principles, measurement results to prove such claims are never published.

At Hattorf, the pillar dimensions were increased considerably, as mentioned above (SCHNEIDER, 1973): the writer is listing pillar dimensions of $225m^2$ (original design), $676m^2$, and $900m^2$; extensive mined-out areas with even larger pillar dimensions (remnant pillars) are shown on his mine map. Apparently, unexpected subsidence caused by the original design soon led to larger pillars which are more effective in controlling subsidence caused by stress relief creep.

However, UHLENBECKER's surface subsidence data are appreciated in view of continuing efforts in East German publications to deny the possibility of surface subsidences above potash mines in the Werra district. According to these obsolete publications, the pillars are designed as stable support elements to achieve stable structural support of the overburden.

When the 1958 rockburst at the Merkers potash mine made changes to previous hypotheses necessary, the "discovery" of near-elastic behavior of the 100-m salt cover was presented, e.g., (SPACKELER et al, 1960, referring to their Fig. 10 (GIMM) and to theoretical calculations by HÖFER, see 2.4 for details).

Such hypotheses are clearly shown untenable by the subsidence data presented in Figures 7-3 through 7-9. It is re-emphasized that the potash mines in the South Harz district are also covered by approximately 100m of rocksalt. It took about a decade until the hypothesis of near-elastic behavior of the 100-m salt cover was officially dropped (GIMM, 1968, p. 205). This change is attributed to "recent surface subsidence measurements" by HOTTEWITZ (1966, not published). It is necessary to resort to the data as reported by GIMM (1968, pp. 255/256):

An isolated mined-out area (no dimensions given) at the depth of 800m was approached "from great distances" by subsequent extraction with "more favorable room and pillar dimensions". These dimensions are not given; however, the less favorable dimensions applied in the mined-out area are given as follows: pillar width 10 and 12m, room width 16m, heights 3-12m, depending on the composition of the potash bed (3m of sylvinite, up to 9m of carnallite with rocksalt layers). The pillars were considerably weakened by gas outbursts; apparently, heavy spalling was in progress. Two years after the mined-out area had to be abandoned, the extraction was resumed "at great distances". No extraction was going on in the underlying second potash bed.

GIMM (l.c., p. 255) emphasizes the danger involved in such extraction sequences: as the tension zone in the subsiding overburden approaches the previously extracted area, sudden subsidence may occur and cause under-dimensioned pillars to fail. Pillar failure constitutes a rockburst according to his hypotheses. The surface subsidence increased considerably when the new extraction front came close to the mined-out area.

Exact data on the development of the surface subsidence are not given; however, GIMM (l.c., p. 256) expresses agreement with the conclusions drawn by HOTTEWTIZ (1966): when an extraction front approaches a previously mined-out area the danger of a rockburst may be imminent.

Considering the known angle of draw, see Fig. 7-1, and the mining depth of 800m, one can see that these conclusions are still based on the assumption of near-elastic behavior of the rocksalt cover. However, surface subsidence becomes measurable several hundred metres ahead of advancing extraction fronts, and the tension zones of both the old and the new mined-out areas begin to overlap. This constitutes a mining situation which may result in a rockburst due to tensile failure of the main overburden, as shown in detail in Chapter 2.

As the conclusions attributed to HOTTEWITZ (1966) are referred to in numerous publications, the apparent need for caution in accepting unsubstantiated conclusions is re-emphasized.

7.2.1.3 Other German potash mining districts

As mentioned previously, surface subsidence measurements became compulsory in most German potash mining districts at the beginning of this century; their purpose was to prove the structural stability of the mines.

With the exception of a few cases of sudden subsidence due to rockbursts, no detailed subsidence data are published; the published data are dealt with in detail in Chapter 2, and indicate the reason why surface subsidence measurements are kept secret: leading German theoreticians who advised both the mining companies and the governmental mine safety authorities have been claiming for decades that the application of their hypotheses results in structurally stable potash mines. After World War II, the two top antagonists - SPACKELER and KEGEL - found themselves in teaching positions at the Freiberg Mining Academy; needless to say that they had students assigned work in potash mines to collect material to prove their respective contradictory hypotheses. Caution in evaluating the publications of either one of the two feuding schools appears indicated, although both schools agreed that structural stability should be achieved in salt and potash mines.

This appears to be the main reason why surface subsidences are not discussed in most German publications: according to theory, all potash mines were structurally stable, and surface subsidence was not supposed to occur. The tendency of denying surface subsidence is particularly obvious in GIMM's (1968) textbook which deals extensively with rock-mechanical aspects of salt and potash mining: the only surface subsidence profile shown is the one published by RUHMANNSEDER (1955); the author is not mentioned.

However, GIMM (l.c., p. 381) claims that surface subsidence measurements after 1950 indicate the continuing decrease in subsidence rates attributed to the backfilling of extracted rooms with refinery waste.

With reference to Figure 7-5, it is re-emphasized here that these theoretical expectations proved wrong, as did similar expectations in cases where no secondary pillar mining and no backfilling were involved. It may have been realized in recent years that surface subsidence above salt mines is inevitable, and is necessary, but harmless if initiated by appropriate extraction sequences.

However, the publications by representatives of the two feuding schools mentioned above should be read with the required caution in mind. After KEGEL's death, the hypotheses of his opponent were temporarily favored, as becomes apparent from HÖFER's (1958a) dissertation, and subsequent dissertations accepted at the Freiberg Mining Academy.

It goes without saying that mining companies, being ordered to keep the overburden above mined-out areas in its original position, are not interested in releasing surface subsidence measurement data which prove the contrary. The situation became different in East Germany in 1947, when the Soviet Military Administration took over most operating potash mines and handed them over to the German Democratic Republic in 1951. At least since that time, the East German theoreticians had unrestricted access to the surface subsidence data accumulated since the beginning of this century. There is no excuse for not using these data in assessing the validity of their hypotheses.

HÖFER (1958a, p. 8), referring to long-term subsidence measurements, admits that surface subsidences were measured above most potash mines. However, the subsidences are attributed to pillar failure due to excess loading. The writer, like most German theoreticians, ignores stress relief creep and considers surficial spalling off pillars as indication of pillar failure due to excess loading.

The subsidence rates listed in Table 2-II are considered as admissable in room-and-pillar mining of salt and potash deposits. When higher subsidence rates are detected, the rooms should be backfilled earlier, or barrier pillars should be left to serve as stable abutments for anticipated stable stress arches. Figure 7-7 was supposed to prove this point; in fact, it proves the opposite; detrimental effects of such "excessive" but gradual surface subsidence are not reported.

Much higher surface subsidence rates are reported (HÖFER, l.c., p. 96) above a carnallite mine with extraction depths of 350 - 400m. Exact data are not given; the surface subsidence is considered relatively small in comparison with measured pillar transverse expansions of up to 4.19 mm/day. This maximum creep rate was measured at a pillar 7.6m high over 82 days. The standard design dimensions are listed as follows: pillar widths 10 - 12m, heights 12 - 14m, room width 11 - 12m.

The extraordinary high creep rates were measured when a remnant pillar 52m wide and 200m long was extracted; apparently, it carried several times the original overburden load. Accordingly, rather rapid stress relief creep and corresponding surface subsidence was inevitable, as shown for another case in Figure 7-8.

"Normal" pillar expansion rates at this carnallite mine reached values up to 480mm/year (HÖFER, 1958, Table 20); vertical convergence rates are not reported and backfilling is not mentioned; extraction sequences also are not indicated. This makes it impossible to predict an exact limiting value of surface subsidence and the time required to reach this value. The pillar height of 12 - 14m and the extraction ratio of approximately 50% indicate a limiting value close to 6m.

Surface subsidence troughs nearly 2m deep are reported in another publication (LÖFFLER, 1963, p. 150) for the same mine, and for an adjacent mine. These subsidences apparently were caused by the extraction of sylvinite lenses several decades previously; it is not reported if these subsidences were still in progress at the time of publication. However, considering the extremely high creep rates reported above for carnallite pillars, there can be no question as to the development of deep subsidence troughs above large mined-out carnallite areas.

GIMM (1968, p. 364 and p. 396) refers to numerous cases where surface subsidence troughs reached depths of up to 2.5m without causing any danger of flooding to the respective potash mines. No details are reported. The writer rather deals extensively with design procedures to achieve stable support pillars in potash mines.

East German publications over the past 15 - 20 years (particularly by GIMM, HÖFER, and their students and co-workers, respectively) are characterized by frequent changes in hypotheses which became necessary because of unexpected consequences of the application of previous hypotheses.

In spite of serious consequences, particularly rockbursts as shown in Chapter 2, leading theoreticians have their students and co-workers praise their obsolete earlier hypotheses; in this way, theoreticians in other countries are misled as they fail to recognize the real nature of such boastful publicity. These explicit statements are considered necessary in view of the potential danger involved in the practical application of hypotheses which promise structural stability of excavations in salt deposits.

This criticism equally applies to numerous publications by DREYER (1955 - 1977) who is endorsing hypotheses promoted by GIMM and HÖFER, but ignores the long-term surface subsidence measurements above German potash mines. It remains to be seen who is going to claim merit for causing the most recent earthquake in the Werra potash mining district in 1975; both DREYER and GIMM claim priority in proposing the design principles which apparently caused this rockburst, see 2.6 for details.

7.2.1.4 Potash mines in the Carpathian foothills, U.S.S.R.

In contrast to the secrecy in dealing with unexpected surface subsidences above German potash mines, Russian publications reveal overburden subsidences which apparently also exceeded theoretical expectations and indicate serious failures.

This is shown in the following discussion of a review by BÖRGER (1971) dealing with surface subsidence measurements above potash mines at relatively shallow depths in the Carpathian foothills (SIVOKON et al., 1970).

The potash deposits of the Carpathian foothills are not embedded in thick salt sequences but represent so-called lenses which formed in local lagoons. The potash beds occur in sequences of saliferous clay with gypsum and anhydrite, and limited amounts of rocksalt. The potash minerals are sylvite, kainite, and kainite-langbeinite. The K_2O - contents of the ore are not given; "clay" contents up to 30% of the extracted ore are mentioned. Some pertinent data are compiled in Table 7-III.

The compressive strengths of the different ore types are listed as 300 and 400 kp/cm^2, respectively. These strength parameters are used in calculating the supporting capacity of pillars (R) according to the formula: (F = compressive strength, a = pillar width, h = pillar height).

$$R = F \sqrt{\frac{a}{h}}$$

Deformations by creep are not taken into consideration. Safety factors are calculated by comparing theoretical pillar loads with theoretical load-bearing capacities.

Surface subsidence data were obtained above 3 deposits extracted near the town of Kalush: the North field, the Chotin field, and the Kainite field.

The reviewer considers the following data as essential in assessing the relationships between extraction and surface subsidence:

In the North field, the total volume of extracted ore was 1.8 x 10^6 m^3. From 1950 to 1956, 0.265 x 10^6 m^3 of waste mine rock were dumped into the excavated rooms. In 1963, 0.5 x 10^6 m^3 of refinery waste were flushed hydraulically into the mined-out area. This resulted in a temporary increase in surface subsidence rates from 140 to 210-350mm/yr. The reviewer considers this temporary increase as a single case not normally associated with hydraulic backfilling. This opinion cannot be accepted, see the evidence presented in 7.2.1.1.

The surface subsidence rates above the mined-out North field are listed as follows: 30 - 60m/year from 1947 - 1957
up to 440m/yr from 1957 to 1963;
30 - 110mm/yr from 1963 to 1966.

Total measured subsidences are not given; the subsidences apparently continue after the last indicated time period.

The limiting value of surface subsidence may be estimated from the difference between the volumes of extracted ore and backfill; this difference exceeds 10^6 m^3.

It is not indicated if the extracted North field was left to flooding, or if it was flooded accidentally when backfilled hydraulically with refinery waste in 1962. The latter appears likely as the report emphasizes that the surface subsidence trough filled with water up to

TABLE 7-III

Potash mines near Kalush, U.S.S.R. Geological data and mining conditions (BÖRGER, 1971, from SIVOKON et al., 1970).

	North field	Chotin field	Kainite field
Type of potash ore	sylvinite	sylvinite	kainite
Depth below surface (m)	170 - 450	150 - 240	100 - 220
Dip (Degree, °)	12 - 42	8 - 15	26
Striking length (m)	1200	700	750
Span of mined-out area (m)	800	300	250
Time of extraction (years)	1946-1961	1961-1969	since 1957
Volume extracted ($10^6 m^3$)	1.8	0.87	not yet known
Extraction ratio (%)	61	60	60-61 in panels
Height of rooms (m)	4.8 - 17.9	16.0	13.1 - 17.8
Width of rooms (m)	11.1 - 12.0	10.7	10.4 - 11.4
Width of pillars (m)	4.2 - 6.9	7.0	6.5 - 14.4
Theoretical pillar load (kp/cm^2)	160 - 190	97	59 - 87
Compressive strength (kp/cm^2)	300	300	400
Load capacity pillars (kp/cm^2)	186 - 282	198	242 - 387
Safety factor R (calculated)*	1.16 - 1.68	2.04	2.78 - 6.56

* see text for formula used in calculation

3m deep, which covered approximately one half of the extracted area.

The extracted Chotin field was not backfilled. The maximum surface subsidence rate is reported as 130mm/yr; it was measured in 1969 above the center of the mined-out area, increasing from the 1966 rate of 22mm/yr. The total measured subsidence is reported as 252mm. The convergence rates were increasing in the center of the mined-out area along with increased spalling off the pillars. These observations indicate that the process of pillar reloading was still in progress; the resistance to deformation of the overburden apparently was decreasing as the subsidence trough became deeper.

With reference to Figure 7-1, and considering the span of 300m of the extracted area at depths from 150 - 240m, it is emphasized here that apparently tension developed throughout the subsiding overburden. The reviewer (l.c., p. 441) refers to fractures and displacements in the center of the Chotin field; these observations may indicate that the maximum subsidence rates had not yet been reached when the report was written.

BÖRGER (l.c., p. 442) stresses the point that the maximum pillar heights of 20m in the North field and of 22m in the Chotin field are extremely disadvantageous in view of the pillar widths of only 5 - 7m. The theoretical width-to-height ratios are of the order of 0.3 - 0.4; they become even more unfavorable with spalling off the pillar surfaces as specifically noted for the central area of the Chotin field (the discrepancy between the maximum given pillar heights and those listed in Table 7-III is not explained).

In any case, pillars possess hardly any supporting capacity. Imminent overburden collapse is indicated by sharply increasing surface subsidence rates in 1969. In this writer's opinion, the collapse of the mine workings was inevitable, and imminent; it may have occurred shortly after the extraction was terminated.

Observations and measurements during the extraction of the Kainite field are of particular interest with respect to the effects of barrier pillars on the development of overburden subsidence. The extraction commenced in 1957 and was nearly completed at the time of publication of the reference paper (1970). Figure 7-10 (BÖRGER, 1971) shows the extracted rooms, most of them extending from the +65m level at the southern boundary to the +190m level at the northern boundary of the field. Numerous breakthroughs in some pillars, particularly in Block 1, should be noticed.

The barrier pillars were left for the purpose of minimizing the effects of extraction on residential areas above the mine. The original plan called for backfilling with refinery waste to improve the hoped-for effect of barrier pillars. However, hydraulic backfilling of the mined-out Block 1 resulted in waste breakthrough into the main roadway at the +65m level. It was decided to terminate the planned backfilling of the subsequent blocks, and to increase the pillar widths considerably, as shown in Figure 7-10 and Table 7-III.

Figure 7-II shows a schematic cross-section of the mined-out

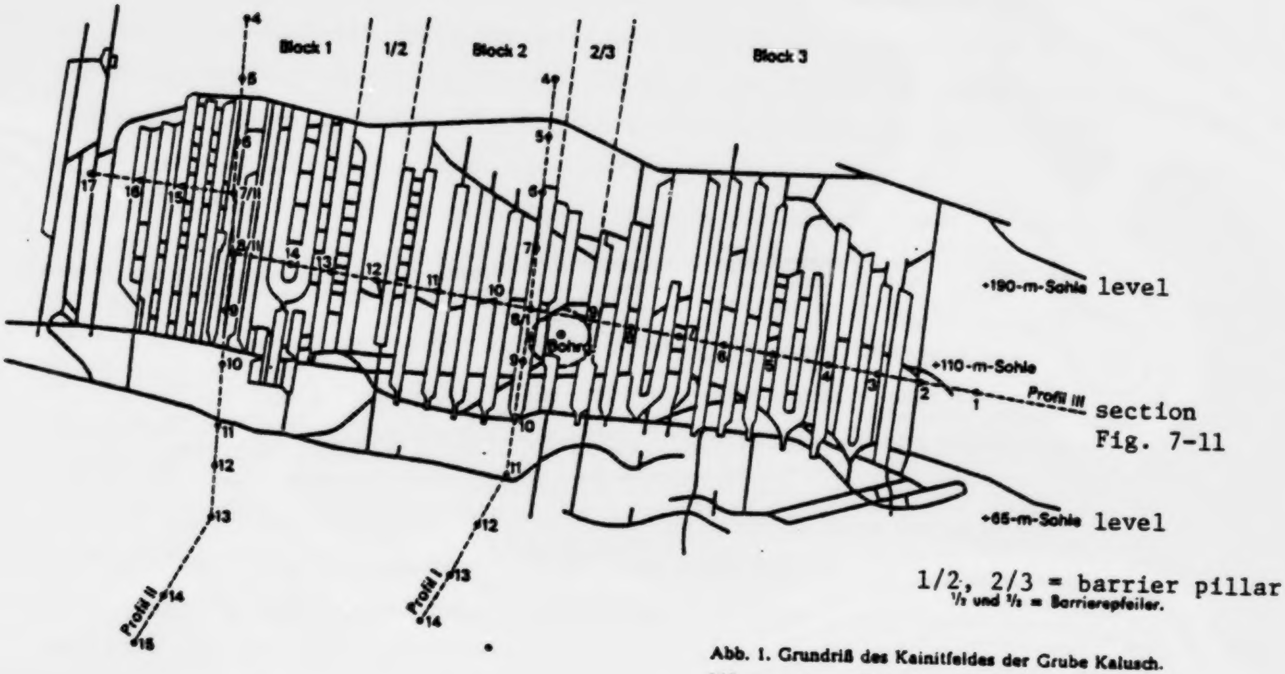


Abb. 1. Grundriß des Kainitfeldes der Grube Kalusch.
Mine map, Kainite field, Kalush

Fig. 7 - 10: Mine map, Kainite field, Kalush, Carpathian foothills.
(BÖRGER, 1971, after SIVOKON et al., 1970)

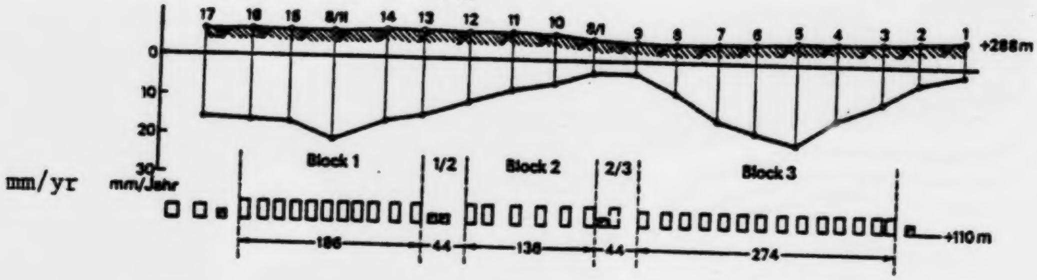


Fig. 7 - 11: Kainite field, Kalush, Carpathian foothills
Section and subsidence rates (BÖRGER, 1971)

entries and rooms at the _110m level, beneath the surface subsidence observation line indicated on the mine map (Fig. 7-10). The maximum surface subsidence rates measured along this observation line are listed in Table 7-III. The subsidence rates measured at individual measuring points are shown as a profile in Figure 7-11.

It is emphasized that Fig. 7-11 shows subsidence rates. It is not known if the subsidence rates are calculated for comparable periods of time. The reviewer fails to indicate the time of the beginning of the measurements. However, the profile indicates the shape of the subsidence trough at the time of the last measurement referred to, i.e., in all probability at the time when the extraction ceased in 1969.

The subsidence characteristics of Figure 7-1 clearly show in the profile of subsidence rates, Figure 7-11. There is, of course, no neutral zone in the center of the subsidence trough as the N-S span of the extracted area reached only 250m, or less, as shown in Figure 7-10. The presence of compression zones appears questionable, i.e., the subsiding overburden remained in tension over the entire measuring period.

At the western boundary of Block 1, the tension zone extends far beyond the boundary of the extracted area; this may, in part, have been caused by the excavation of two openings with rather large cross-sections outside of Block 1, see Figure 7-11. The purpose of these openings is not indicated in the reference paper; apparently, they are inclines from the surface.

The regular decrease in subsidence rates from the center of Block 1 to the barrier pillar 2/3 clearly reflects the greater pillar widths underneath this area; apparently, the above-mentioned mishap - breakthrough of backfill - occurred when about one half of Block 1 had been extracted, prompting the decision to increase the pillar width from 5 - 7m to 15m in the rest of Block 1, and in Block 2.

The so-called barrier pillars had little, if any, effect on the development of the surface subsidences. The causes are apparent: two openings shown in the barrier pillar 1/2 (Fig. 7-10) were excavated throughout the length of the barrier pillar. The barrier-pillar 2/3 also was partly extracted, with the exception of a borehole safety pillar indicated on the mine map. This borehole safety pillar appears to be the principal cause of relatively small subsidence rates above the nominal barrier pillar.

The overlapping tension zones above the barrier pillar 2/3 are indicated by relatively small subsidence rates. This constitutes a rock mechanical situation which may cause problems when tension fractures develop; when fractures are suddenly torn apart, such failures manifest themselves as rockbursts, as repeatedly emphasized, see Chapters 2 and 3.

In this particular case of the Kainite field, the geological situation is exceptionally hazardous as salt strata with sufficient thicknesses are not present above the mine workings. For this reason, the development of the separate subsidence trough above Block 3 is considered indicative of impending serious water inflow.

As the development of the surface subsidences is not reported, there is no point in discussing possible reasons for the rather high subsidence rate above Block 3 in comparison with those above Block 1.

The theoretical safety factors listed in Table 7-III have little, if any, significance as the theoretical supporting capacities of pillars are meaningless because of stress relief creep. It appears unlikely that the pillars in Blocks 1 and 3 are loaded with the theoretical loads according to depth and extraction ratio; this follows from the wide overlapping of the subsidence trough onto non-extracted ground around the mined-out blocks. At the time of the last reported measurements, abutments for the subsiding overburden formations were still provided by non-extracted ground. In view of the apparent creep deformations indicated by spalling off the pillar surfaces in the central areas of the mined-out blocks, the Kainite field is bound to share the fate of the North field: the sooner groundwater gains access to the mine workings through tension cracks, the sooner the mine will be flooded.

In this way, many salt and potash mines at shallow depths were lost as shown in 3.2. However, no detailed subsidence data are available such as discussed in the foregoing to show the subsidence characteristics, and the related failure mechanisms.

7.2.2 Panel-and-pillar mines

7.2.2.1 Mine Fernand, Alsace, France.

Some experimental panel-and-pillar mining at the Mine Fernand is discussed in detail in I/5.4.2, pp. 237-247.

Fig. I/5-18 shows a longitudinal section and the initial development of a typical surface subsidence trough along the observation line indicated on Fig. 7-12. Structural stability apparently did not materialize as expected on the basis of hypotheses which call for stable stress arches to be supported by stable abutments. The surface subsidence profiles demonstrate overburden settlement following the panel extraction without delay.

Such immediate reaction is attributable to the fact that the area to the NE of the panel-and-pillar block was extracted previously; the existing subsidence trough extended to the SW when the experimental panel-and-pillar mining removed the abutment to which bridging overburden formations were still transferring some overburden load.

Apparently, lateral creep out of room and floor of the interpanel pillars made the unexpected subsidence possible, as outlined in I/5.4.2. In other words: the subsidence was safely controlled by creep deformations; in June 1963, the maximum subsidence of approximately 100 mm was measured above the interpanel pillar 102/104 with the smallest width of 50 m.

Fig. 7-1~~9~~2, a simplified mine map, shows the widths of panels (with numbers) and barrier pillars in the experimental block, the surface subsidence observation line, and depth contour lines (WARDELL, 1968). The previously extracted area is indicated according to written information (Laperriere, Mines de Potasse d'Alsace, Mulhouse). The four-entry system along the southern boundary of the experimental block is not shown; for these and other details, the reader is referred to the maps published by McCLAIN (1964).

The extraction sequence in the experimental block is quoted from WARDELL (1968) in I/5.4.2, pp. 238 - 240: "panels 110 and 114 were begun first, followed later by panels 108 and 112. The southern part of panel 112, and the panels 102, 106, and 104 were extracted completely, while the small pillars in the other panels were left". The total

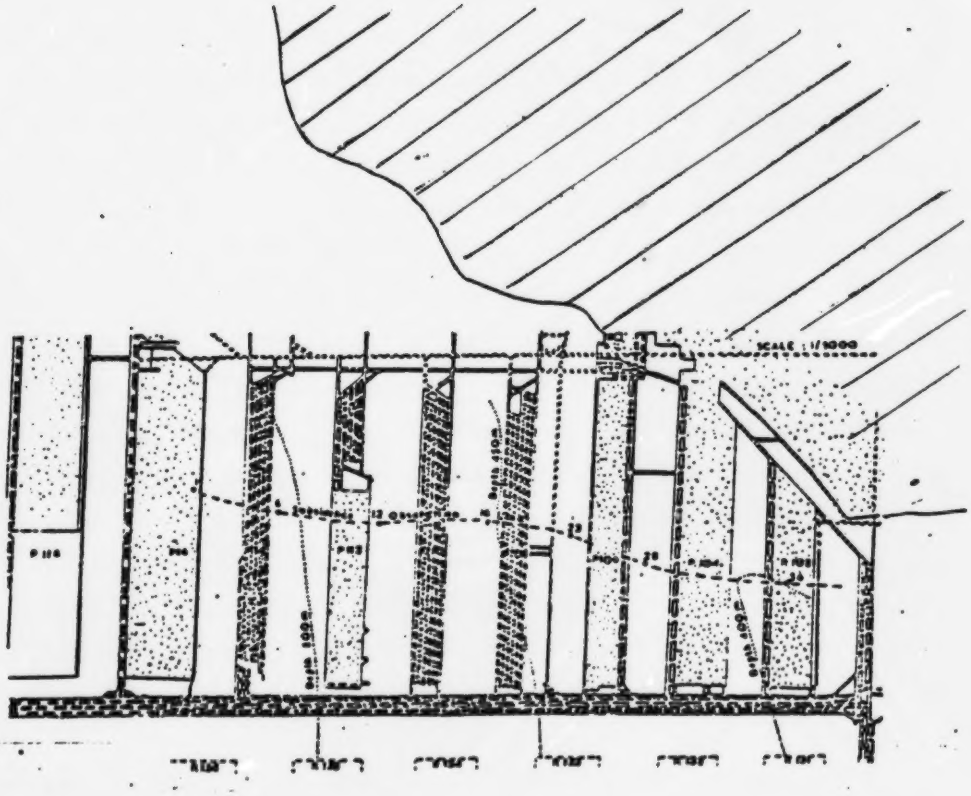


Fig. 7 - 12: Mine Fernand, Alsace, France
Experimental panel-and-pillar mining (WARDELL, 1968)

extraction of panels 102 and 106 is reflected in the subsidence profile measured in June 1963, see Fig. I/5-18.

In June 1963, the face of the last extracted panel 104 advanced over the surface subsidence observation line; the resulting local deepening of the subsidence trough shows in the subsidence profile measured in August 1963. The maximum subsidence during 2 months is approximately 40 mm, the subsidence rate is approximately 240 mm/year. The immediate reaction of the whole overburden is evident; the surface subsidence rate is much higher than those listed in Table 7-I for room-and-pillar mines at similar depths.

The subsidence measurements were discontinued because of development work in the area. The maximum measured surface subsidence of less than 200 mm until August 1964, compared with the thickness of 2.88 m of the extracted potash bed, is definitely not "the finally observed surface subsidence" (WARDELL, 1968, p. 278). The writer (l.c., p. 279) believes "that it will be possible to achieve an overall extraction rate of 65 - 70 per cent at this depth and still maintain stability and control."

It is agreed that control of the subsidence was achieved; however, stability cannot be expected before the limiting value of subsidence is reached, see Fig. 7-1. As the future extraction sequence is not known, any further discussion appears pointless.

However, the subsidence control mechanism needs an interpretation as the stress arch concept cannot be applied in salt deposits for reasons given in Chapters 2 and 3.

Some important points regarding "the mechanism by which these pillars (the interpanel pillars) provide support for the overlying strata" (McCLAIN, 1964, p. 194) are discussed in detail in I/5.4.2, pp. 244-247. It is re-emphasized that stress-relief creep immediately after any excavation is the most important single mechanism which must be taken into consideration; stress relief creep zones are travelling ahead of advancing extraction fronts, particularly in cases where faces advance slowly, providing ample time for stress relief creep to cause lateral deformations out of roof and floor of faces and remaining large pillars.

As pointed out in I/5.4.2, p. 245, "considerable creep above and below the large interpanel pillars can be assumed, particularly after roof caving which increases the effective pillar height considerably."

The shift to total panel extraction, after approximately one half of panel 112 had been extracted with small panel pillars left in place, appears to have enhanced considerably the effects of stress relief creep during the extraction of the three remaining panels 102, 106, and 104. The extraction of the last panel, 104, is characterized by typical effects of extraction in remnant pillars, see I/5.4.2.

It may be emphasized here that the intentional roof caving practised in panels 102, 106, and 104 represents an independent overburden subsidence control mechanism, provided that the immediate roof strata can be forced to cave along pre-determined caving lines; the loosening factor (bulking factor) of the caved roof rock may be sufficient to provide immediately some restraint against underground subsidence and/or floor uplift. Recompression of the broken rock mass requires increasing loads of subsiding overburden, controlling in this way the surface subsidence rates. This topic is dealt with in more detail in 7.4, and particularly in 8.3.

Due to the lack of measurement data regarding both the extent of stress relief creep immediately after excavation and the extent of caving into the immediate roof, any further discussion of the mechanism which caused the decrease in surface subsidence rates above the experimental block at the Mine Fernand could only be based on assumptions.

With reference to the detailed discussion in I/5.4, it is reemphasized that the effects of stress relief creep and of reloading creep must be considered adequately in any interpretation of measured surface subsidences.

7.2.2.2 PCS Rocanville (formerly Sylvite), Saskatchewan, Canada

The public controversies at the Fourth International Symposium on Salt, Houston, Texas, 1973 (PIPER, 1974) were triggered by misleading publications (SERATA, 1966, 1968, 1970, 1972, 1973, particularly 1974; SERATA and SCHULTZ, 1972; SCHULTZ, 1971, 1973). As the discussions in I: 162-167, 196, 218-220, 226, 248, are based on the cited publications, correct data on design and development of the former Sylvite mine are to be presented in the first place; this was made possible by the recent publication by LOPEZ (1977), and by correct data provided by the mine management after it was confronted with proof of apparent plagiarism.

Figs. 7-13 and 7-14 are examples of the disputed mine layouts which cannot be reconciled with facts. Other published data (SERATA and SCHULTZ, 1972) need even more corrections; the writers, having procured copies of a confidential IMC report (BAAR, 1970b) by rather contemptuous means, kept changing data from publication to publication.

The original design parameters for entry systems are compiled in Table 7-IV.

Figs. 7-15, 7-16, and 7-17 were provided by the mine management in 1973, indicate the changes in design parameters for the first extraction block; it was particularly stressed that the production rooms are only 65 ft. (19.8 m) wide, not 67 ft. (20.4 m) as listed on the maps, and in Table 7-V which summarizes the changes.

TABLE 7-IV

PCS Rocanville (formerly Sylvite), Saskatchewan, Canada

Depth below surface: 3140 ft. (957 m)

Design parameters for main and block entry systems:

Entry width: 45 ft. (13.7 m) Entry height: 8 ft. (2.4 m)

Pillars (2 in main entry system, 1 in block entry system) 335 ft. (102.1 m) wide

Extraction sequence: block development entries cut at right angle from main entries to block boundary; extraction rooms cut in retreat parallel to main entries.

TABLE 7-V

PCS Rocanville (formerly Sylvite), Saskatchewan, Canada

Changes to design widths, block 1; actual room width 65 ft. (19.8 m)

Time	Rooms (ft.)	Rooms (m)	Yield pillars (ft.)	Yield pillars (m)	Barrier pillars (ft.)	Barrier pillars (m)	Remarks
Jan.1970	67	20.4	30	9.1	310	94.5	Design not used
Jan.1972	67	20.4	125	38.1	310	94.5	Only 2 "yield" pillars, see text.
Dec.1972	67	20.4	50	15.2	180	54.9	7 room-pillar-room units (panels)

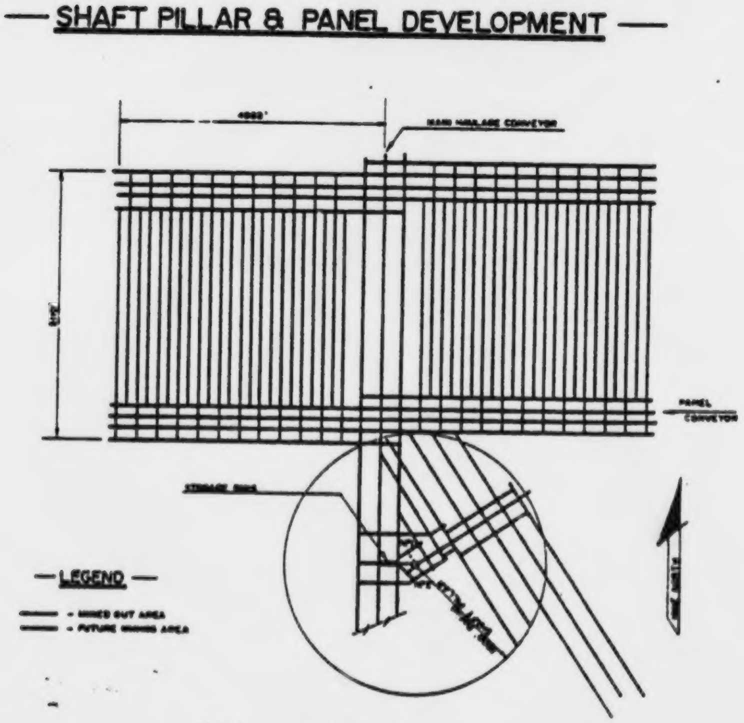
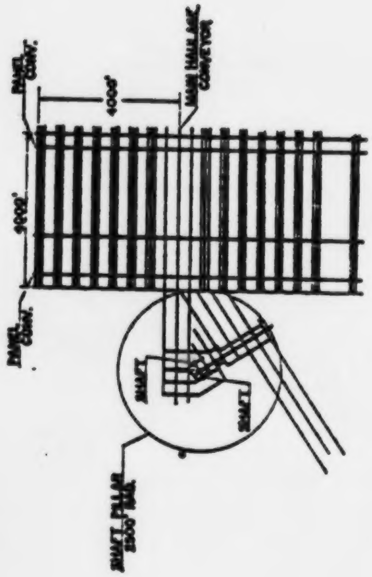
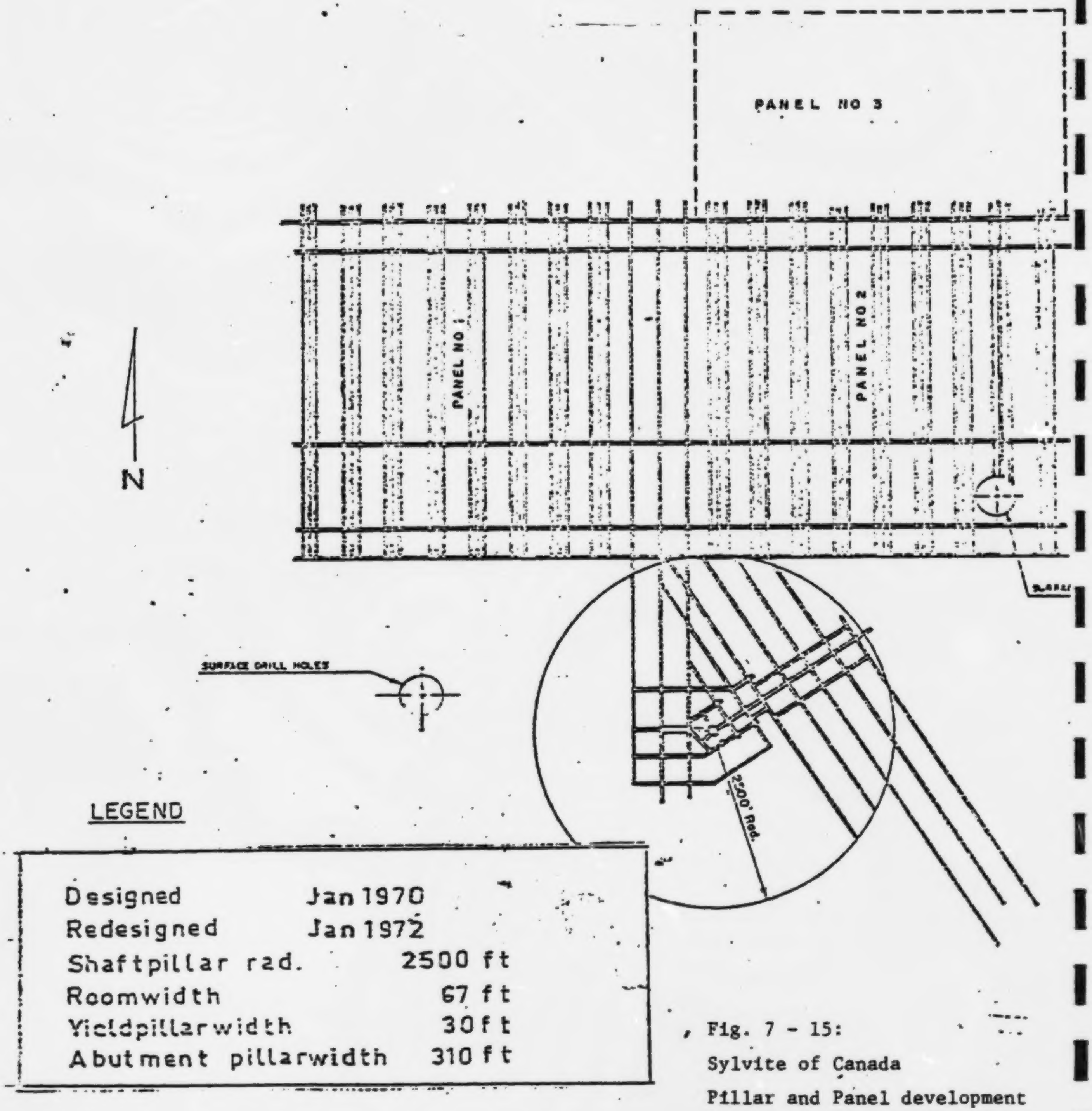


Fig. 7 - 13: PSC Rocanville, formerly Sylvite
First development plan (SCHULTZ, 1971)

Fig. 7 - 14: PSC Rovanville,
formerly Sylvite
Another development plan
(SERATA and SCHULTZ, 1972)





LEGEND

Designed	Jan 1970
Redesigned	Jan 1972
Shaftpillar rad.	2500 ft
Roomwidth	67 ft
Yieldpillarwidth	30 ft
Abutment pillarwidth	310 ft

Fig. 7 - 15:
Sylvite of Canada
Pillar and Panel development
Design January 1970

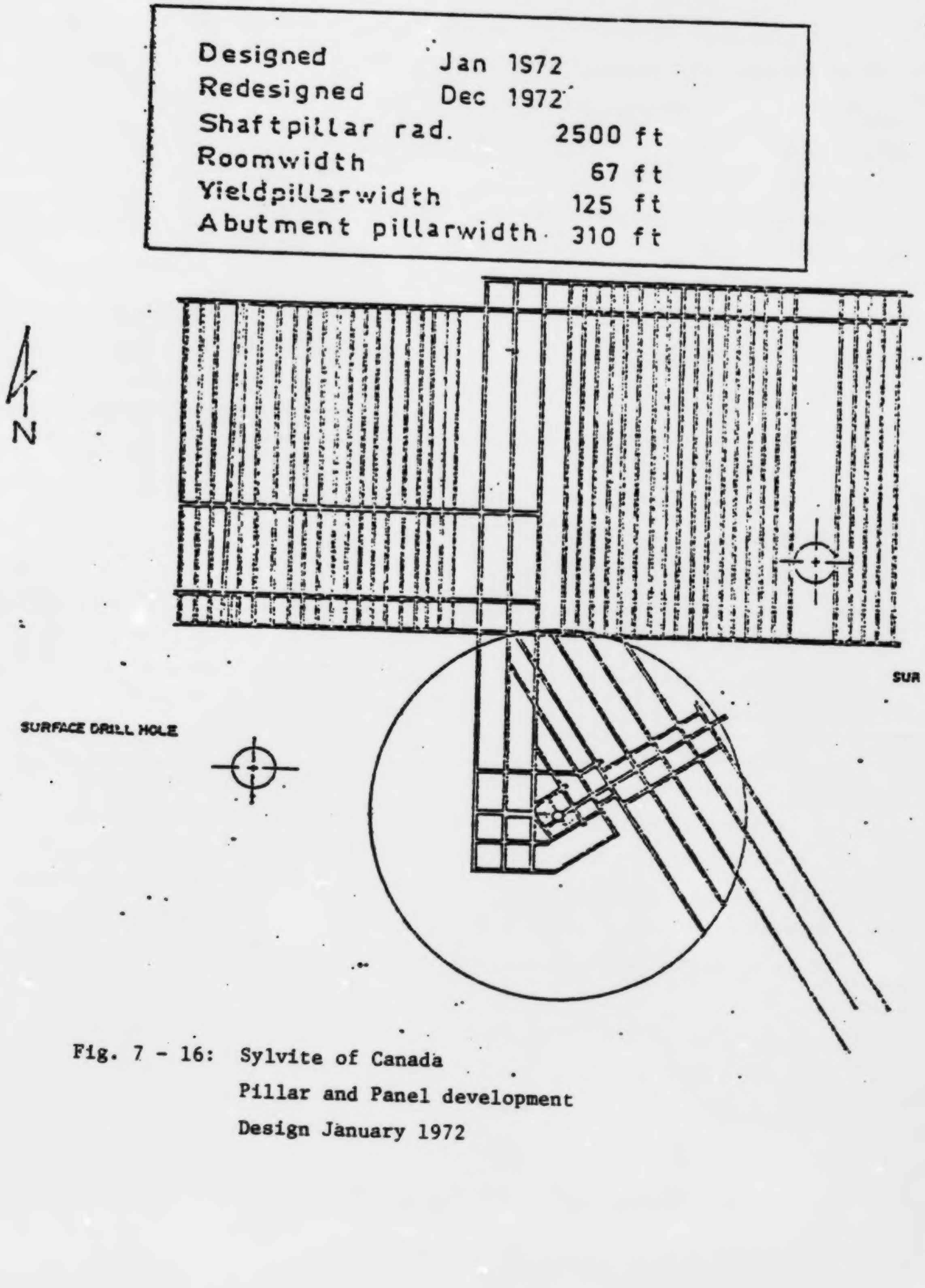
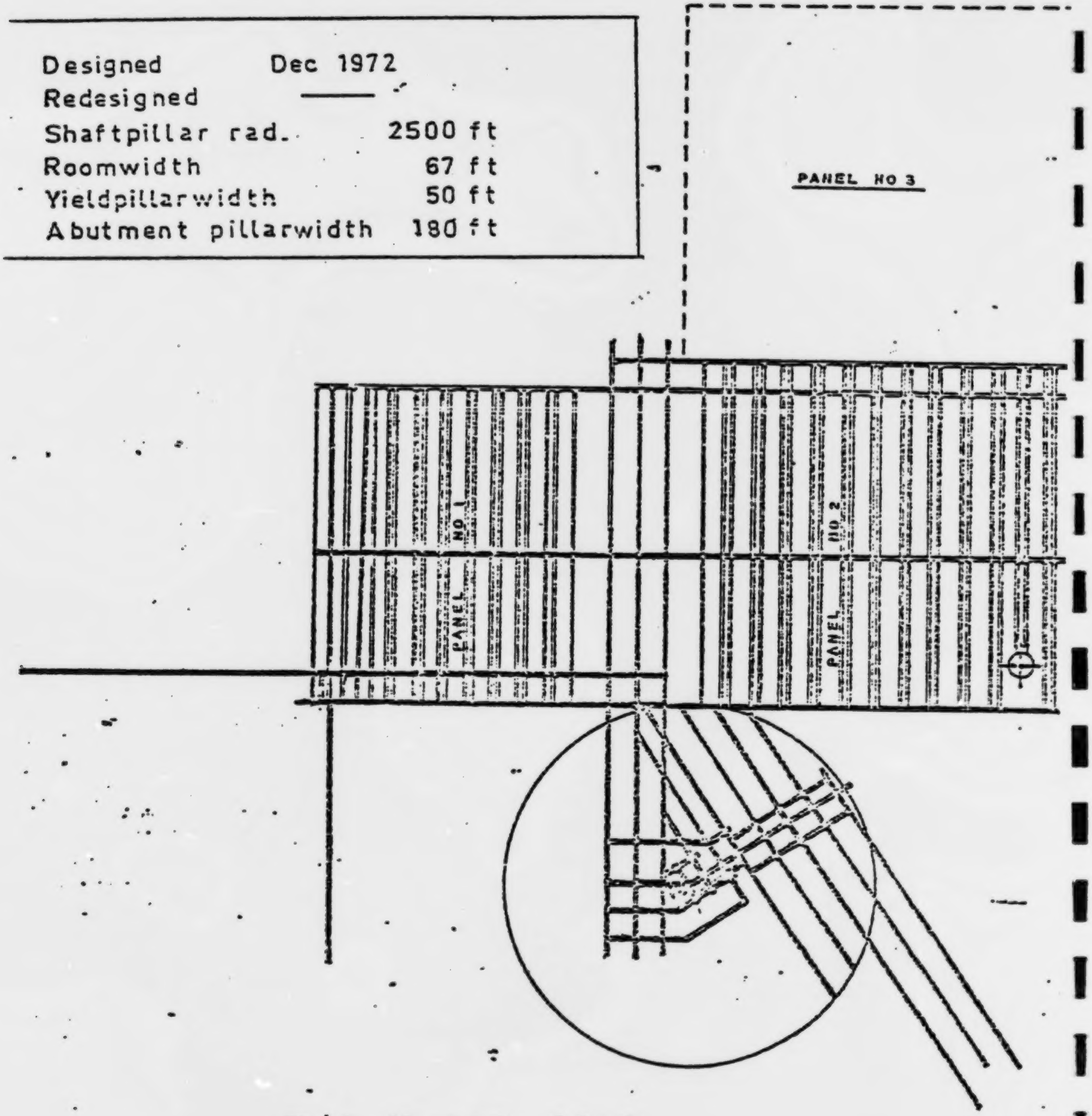


Fig. 7 - 16: Sylvite of Canada
Pillar and Panel development
Design January 1972



Designed	Dec 1972
Redesigned	———
Shaftpillar rad.	2500 ft
Roomwidth	67 ft
Yieldpillarwidth	50 ft
Abutment pillarwidth	180 ft

Fig. 7 - 17: Sylvite of Canada

Pillar and Panel development, designed Dec. 1972

It was emphasized that "there are only three 50-ft wide yield pillars left in between rooms. These yield pillars, in one case 300 ft. long, in the other 700 ft. long, serve as testing areas with installed observation stations. Since data obtained by observations indicate fair ground conditions, it is planned to leave 50 ft. wide yield pillars in between every two 65 ft. wide rooms."

This is a typical panel-and-pillar design, with panels 65 + 65 = 180 ft. wide and barrier pillars also 180 ft. wide. This new design was adopted in December, 1972, see Fig. 7-17.

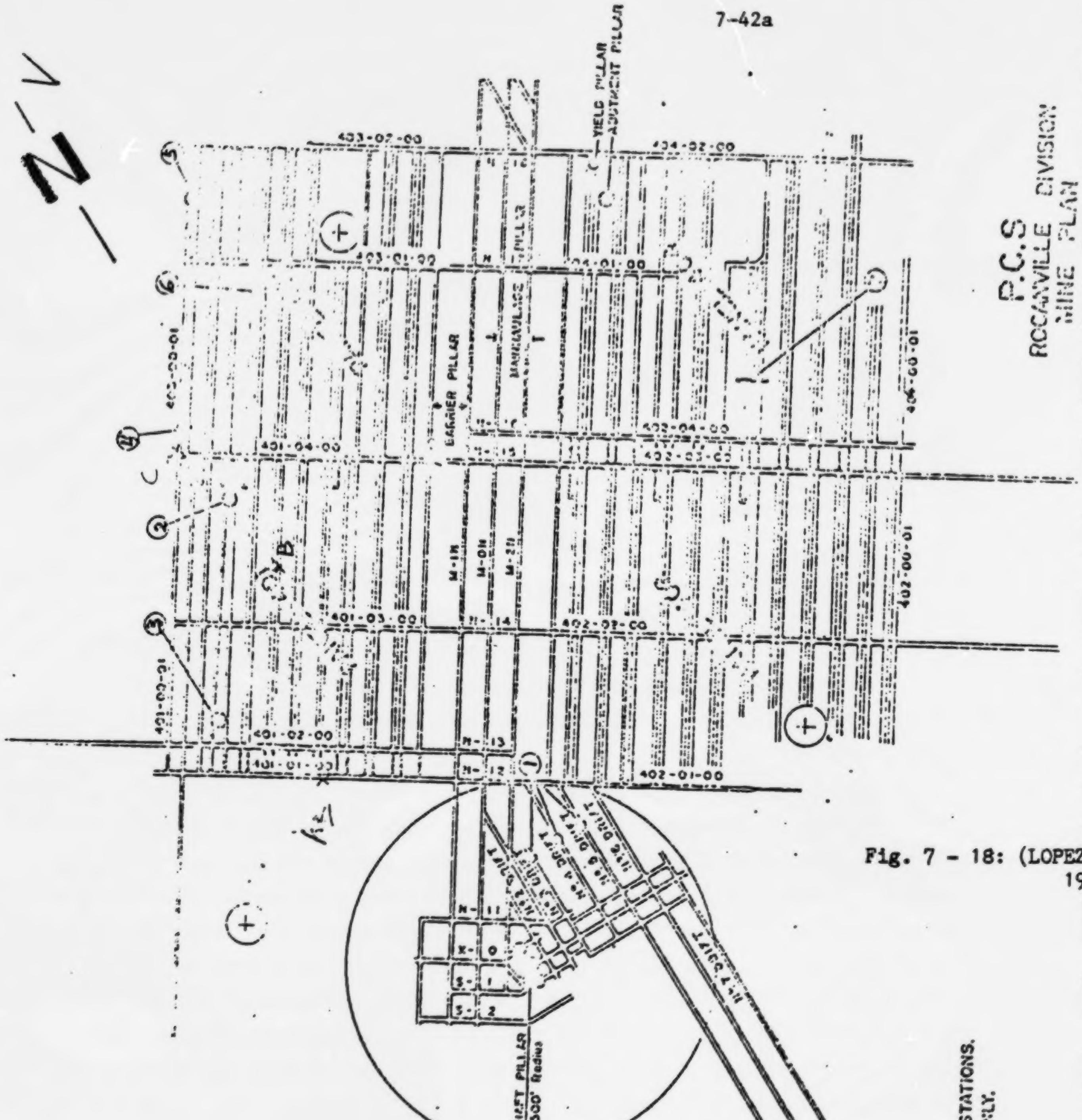
The dimensions adopted in December 1972 were also used in the 3 remaining blocks of the extraction mining area, with the exception of test panels in blocks 3 and 4 consisting of 3 rooms and two 25 ft. (7.6 m) yield pillars, see Fig. 7-18 (LOPEZ, 1977).

The design shown in Fig. 7-17 is not flexible as it should be if and when barren ore zones are encountered or borehole safety pillars are to be left. Safety pillars are indicated by circles (e.g., Fig. 7-18); other areas were left unextracted because of poor ore quality.

The reader is advised of differences in the terminology used in this text to comply with the terminology used in most publications, see Table 7-VI.

The term "abutment pillar" apparently was chosen according to SERATA (1972) to indicate the full support of postulated stable stress arches across room-pillar-room units. The roof arches are supposed to join equivalent floor arches to form stable "stress envelopes". The measurement data to be presented in the following discussions cast particular doubt on the feasibility of 25-ft. (7.6 m) yield pillars in test panels with three 65 ft. (19.8 m) rooms and total spans of 245 ft. (74.7 m), the width of the barrier pillars being reduced accordingly. These doubts, arising from the water pressure in roof strata, are to be discussed later.

The surface subsidence and convergence data (LOPEZ, 1977) fully support this writer's concern about the feasibility of yield pillars which are too narrow, see I/5.3.3, pp. 218/219, and particularly I/4.4.2, pp. 164-167.



ROOM WIDTH	65'	65'	65'	65'
ABUTMENT PILLAR	120'-180'	180'-190'	120'-200'	150'-205'
YIELD PILLAR	30'	50'-40'	50'-25'	50'-25'
BARRIER PILLAR	453'	530'	455'	460'
MAINHAULAGE PILLAR	335'	335'	335'	335'

LEGEND
⊙ INTERNAL & EXTERNAL STATIONS.
—○ EXTERNAL STATIONS ONLY.
○ TEST AREA

Fig. 7 - 18: (LOPEZ 1977)

TABLE 7-VI

Differences in the terminology used in this text and by LOPEZ (1977)

This text	LOPEZ (1977)
Block, e.g. 401	Panel, e.g. 401
Barrier pillar	Abutment pillar
Protective pillar Entry protection pillar	Barrier pillar
Pillar in main entry system	Mainhaulage pillar
Panel	Room-pillar-room unit

A. Convergence data

In the first place convergence data collected in block 1 are presented and discussed. With reference to the typical stress relief creep curves shown in I/6.2.1 the significance of rapid initial stress relief creep is re-emphasized. Stress relief creep into 65 ft. (19.8 m) wide extraction rooms accounts for up to 7 inches (17.8 cm) of convergence within a few days after cutting the final width in virgin ground.

Such stress relief convergences do not show at the surface as they indicate the increase in volume of the salt rocks which participate in stress relief creep into the new excavation, as shown in detail in I/4 and I/5.

The following relationships must be considered:

1. The intersection effect, see I/5.3.1, p. 210: it causes less stress relief convergence at intersections compared to locations at some distance into long-pillar panels.
2. The umbrella effect, see I/5.2.1: along the boundary of a mined-out area, the reloading of stress-relieved pillars may be delayed, depending on the behavior of the overburden.
3. The effect of abutment zones around developing mined-out area: depending on the additional overburden load supported in abutment zones, the initial stress relief creep rates increase considerably and may result in much higher stress relief convergence.
4. Abutment zones travel ahead of advancing extraction fronts; abutment loads increase with the increase in spans of mined-out areas until the overburden subsidence is fully controlled by creep after reloading of the panel pillars which must serve that specific purpose.

Long-term convergence measurements such as shown in I/5.2 are not available for the PCS Rocanville (Sylvite) mine.

Fig. 7-19 demonstrates the development of vertical convergences measured at 1/2 year intervals in the intermediate development entry of block 1 (entry 401-03-00 of Fig. 7-18). The entry was cut 45 ft. wide during the months of November and December of 1971. Retreat mining of the rooms which intersect the development entry started in February 1972. This means that the first closure profile, measured in January 1972, indicates stress relief creep under virgin ground conditions.

The measured total closure until January 1972 reached over 5 inches (12.8 cm) in the future main entry protection pillar, station 1, decreasing regularly to less than 4 inches (10. 6 cm) at station 14 near the opposite block boundary. This decrease in measured total closures reflects the time needed for cutting the second pass of the entry. It is not known how much initial stress relief creep is missing as it commenced when the first pass was cut; measurements could not be taken before the second pass was cut.

The July 1972 profile reflects the cutting sequence of rooms 1 - 4. The rooms 1, 2, and 4 were cut to the full 3-pass width of 65 ft. (19.8m) before July, while 3 was cut later. For this reason, station 13 shows less closure as the intersection effect is missing. The closures measured in January 1973 cannot be related to stress relief creep only. Apparently, heavy reloading had already taken place at station 13. Stations 11 and 12 also indicate some reloading, as the total closures are slightly higher than those measured at stations 1 - 10. Station 13, located at the intersection of 4oom 3, shows the highest total closure attributable to stress relief creep.

These measurement results clearly show that the excavation of room 3 initiated overburden load redistribution to the abutments of the 5 rooms, which existed after November 1972. The pillar in between rooms 2 and 4 was originally approximately 115 ft. (35 m) wide to leave space for the excavation of room 3 according to the design principles promoted by SERATA (1972). Apparently, the 115 ft. pillar was carrying the full overburden load according to depth and extraction ratio.

With reference to I/5.2.1, particularly to pp. I/192/193 and Fig. I/5-3, it is emphasized that these conclusions are in agreement with

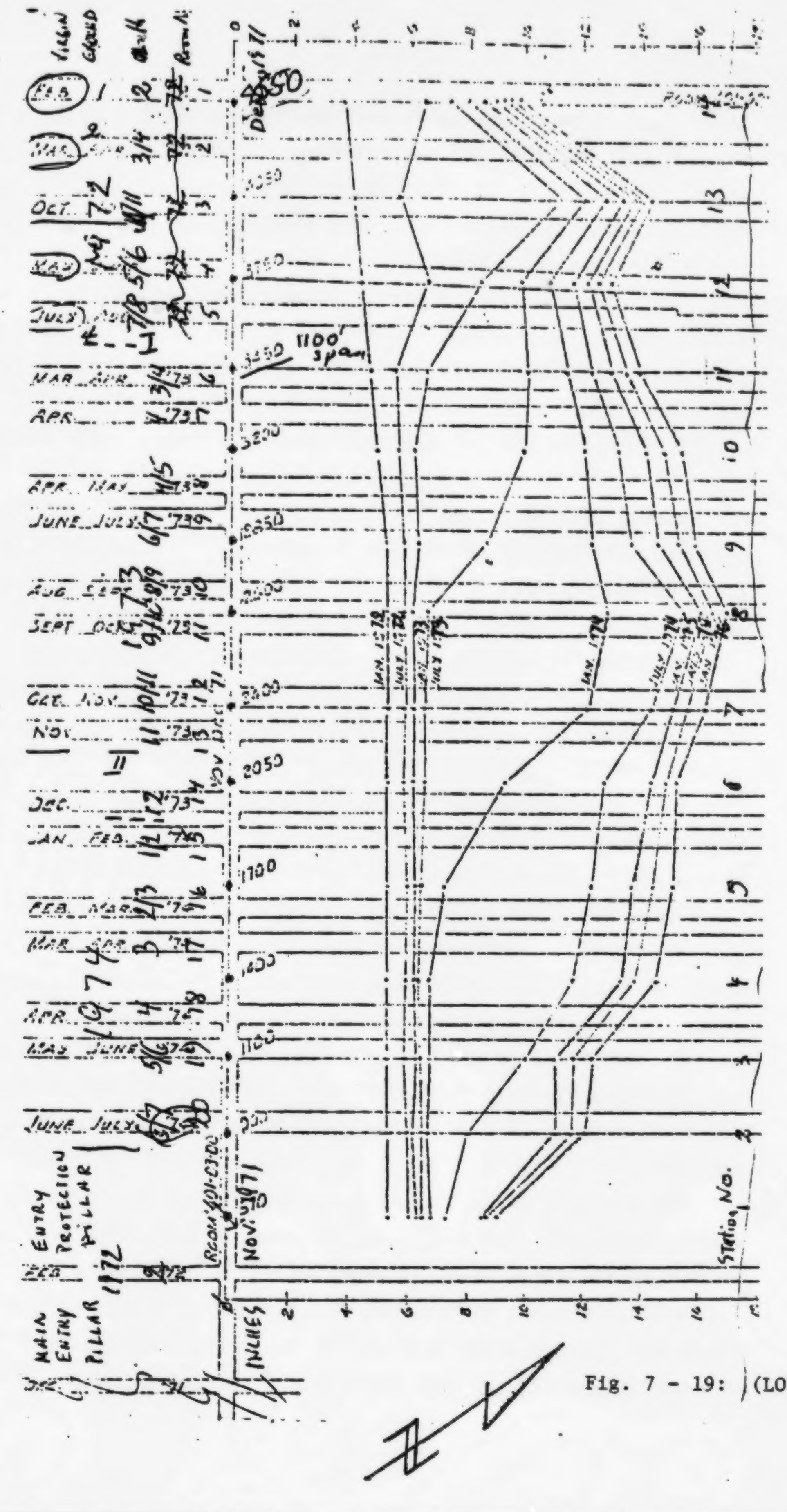


Fig. 7 - 19: (LOPEZ, 1977)

those drawn from measurements and observations at the neighboring IMC mines. The stress relief mechanism shown for a 52-ft. pillar explains why a 115-ft. pillar of equal height is only partly affected by stress relief creep. The extent of stress relief creep into pillars of that height is known to be limited.

The July 1973 closure profile demonstrates the shift of rapid stress relief closure to stations 11, 10, and 9, due to the resumption of extraction mining in the abutment zone of rooms 1 - 5: rooms 6 - 9 were cut prior to measuring the July 1973 closures.

It should be noticed that the location of stations 9 and 10 differs from the location of stations 11 - 14 with respect to the proximity of the nearest intersections. As a matter of fact, station 10 is located at the center-line of the barrier pillar between panels 6/7 and 8/9, i.e., at the distance of 90 ft. (27.4 m) from the adjacent panels which were excavated in April, and in April/May 1973, respectively.

As stress relief creep is not expected to extend to the center of a 180-ft. pillar, the closure of more than 3 inches (7.6 cm) at station 10 is interpreted as reloading creep, including lateral creep above and below the barrier pillar.

This interpretation is supported by the observation of little reloading creep at stations 8 - 6 which are located in the abutment zone of the area extracted until July 1973. In other words: the abutment loads remained approximately equal; the load of the overburden above the extracted area was fully supported by the barrier pillars left in the mined-out area; overburden subsidence was fully controlled by lateral creep of the barrier pillars and their roofs and floors.

At this stage of block extraction, the span of the extracted area was approximately 1550 ft. (472.4 m). The significance of these observations is discussed later in comparison with measured surface subsidences.

The analysis of the convergence profiles of Fig. 7-19 is continued with the closure profile measured in January 1974. The profile shows continuing reloading creep at stations 9, 10, 11, and 12.

Station 8 shows the maximum creep closure, totalling over 12 inches (30.5 cm); approximately one half of it is attributed to the extraction of rooms 10 and 11, the rest may reflect reloading creep due to mining rooms 12 and 13 from October to November, 1973.

Stations 6 through 4 show reactions similar to those measured in January 1973 at stations 13 through 10. It should be noticed that station 4, like station 8 in July 1973, indicates hardly any increase in abutment loads, confirming the interpretation based on the July 1973 closure profile: abutment loads did not increase; however, the abutment zone kept travelling ahead of the extraction front.

The July 1974 convergence profile shows continuing reloading at stations 6 through 12. Station 8 in the center of the mined-out area became the center of the underground convergence trough. Stations 5 and 4 show the maximum closure as previously measured in the abutment zone of the mined-out area.

Stations 2 and 1 show increased closures caused by abutment loading creep, the abutment zone coming close to the first main entry. Station 2 shows additional effects of stress relief creep due to the excavation of the last single room of the block in June/July 1974. The January 1974 survey shows the maximum closure at station 2, apparently due to abutment loading after the July 1974 survey.

The January 1975 profile shows the reloading process continuing at stations 1 through 6. Stations 7 through 11, indicate very little reloading, as the distance to the July 1974 profile is only slightly greater than the distance at stations 12 through 14. At the latter stations, the reloading process was terminated, as indicated by the equal distances between the following closure profiles.

The constant convergence rates indicate creep under full overburden loads.

The July 1975 and January 1976 closure profiles show the reloading process terminated at all stations; the distances between the profiles remain virtually equal. Station 1 exhibits the smallest constant closure rate; apparently, abutment loads resulting from the extraction of block 1 no longer exist.

Stations 12 through 14 also exhibit very small constant closure rates which may reflect the greater width of the pillar between rooms 3 and 4, and the smaller extraction ratio in the area of the first 3 rooms.

Umbrella zones as observed in the early profiles apparently are no longer effective in 1975. The barrier pillars left in the extracted block fully support the deadweight of the overburden; creep as shown in Figs. I/5-2 and I/5-3 effectively controls the overburden subsidence.

It goes without saying that zones of additional abutment load around a mined-out area cease to exist if and when pillars support the full deadweight of the overburden.

Apparently, the lateral stress relief creep out of roof and floor of barrier pillars into newly excavated panels is also characterized by an initial decrease which resembles the decrease in creep rates shown for single openings in I/4.

Fig. 7-20 compares the results of two independent closure surveys in the same intermediate block entry. In March 1976, the actual heights of the openings were measured at the indicated points. As the original cutting height is known, to total closures as of March 1976 can be calculated. The results are plotted together with the last profile of Fig. 7-19 (January 1976). The two profiles "show a good correlation" as stressed by LOPEZ (1977).

This writer considers the March 1976 survey as more reliable because it comprises more points in the critical area near station 13 of Fig. ~~8~~7-19. As shown in the preceding detailed analysis, the exact location of any measuring point with respect to intersections must be considered.

B. Effects of pillar size.

The March 1976 survey of closures reached at that time was carried out throughout the mined-out block 1. Plotting the data on a block plan resulted in the total closure contour plan shown as Fig. 7-21. Its analysis reveals some important relationships between the room and pillar widths, the mining sequence, and the development of convergences.

Extraction mining in retreat began in February 1972, see Fig. 7-19. Until July 1972, some experimental extraction mining using various pillar dimensions was done as discussed previously.

The total closure contours of Fig. 7-21 demonstrate effects of room and pillar dimensions. The 15 and 16 in. contour lines extend from the central area to the fifth intersection of the block entry system. From this intersection back to the main entry system, the cross-cuts in the block entry system have single-pass widths and the barrier pillars in the block entry system have the width of 180 ft. (54.9 m) plus the

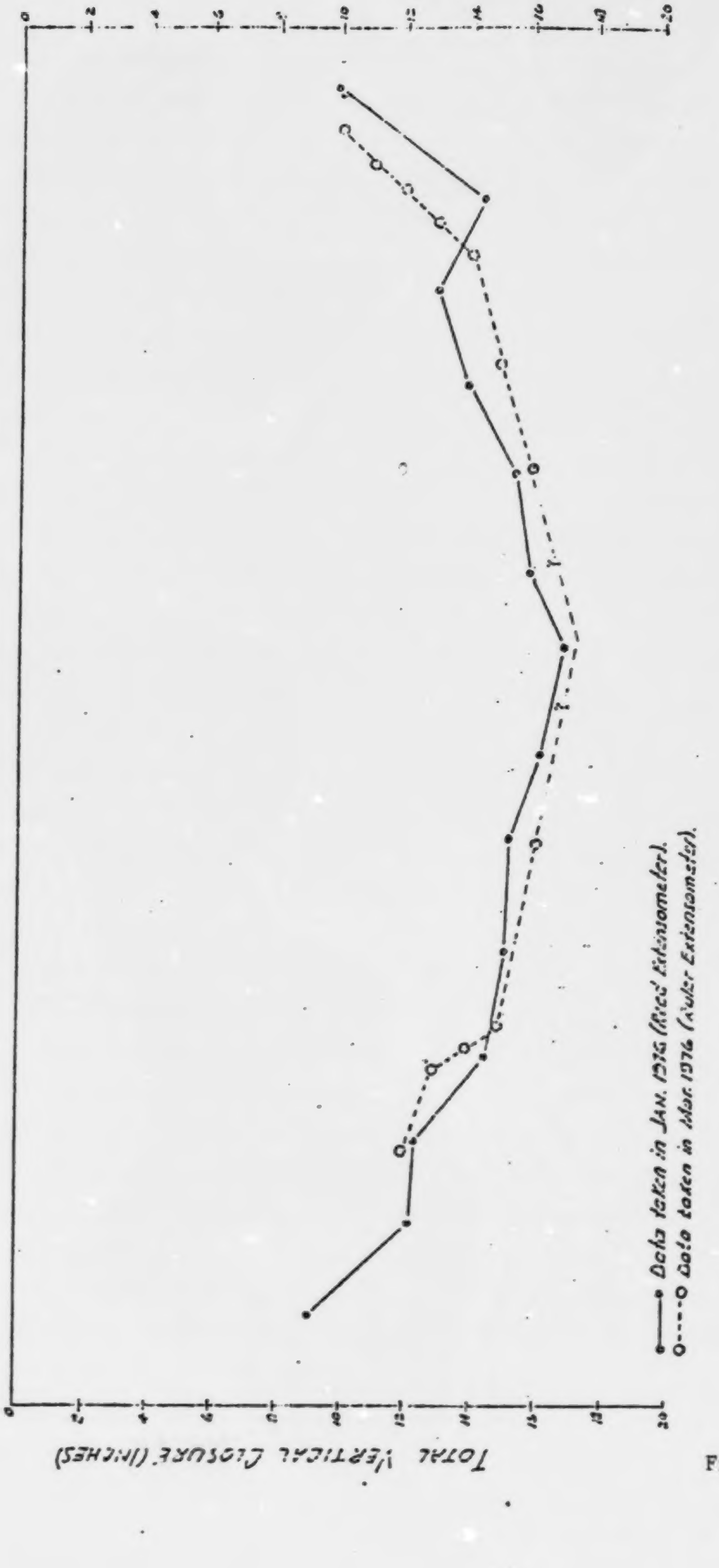


Fig. 7 - 20: (LOPEZ, 1977)

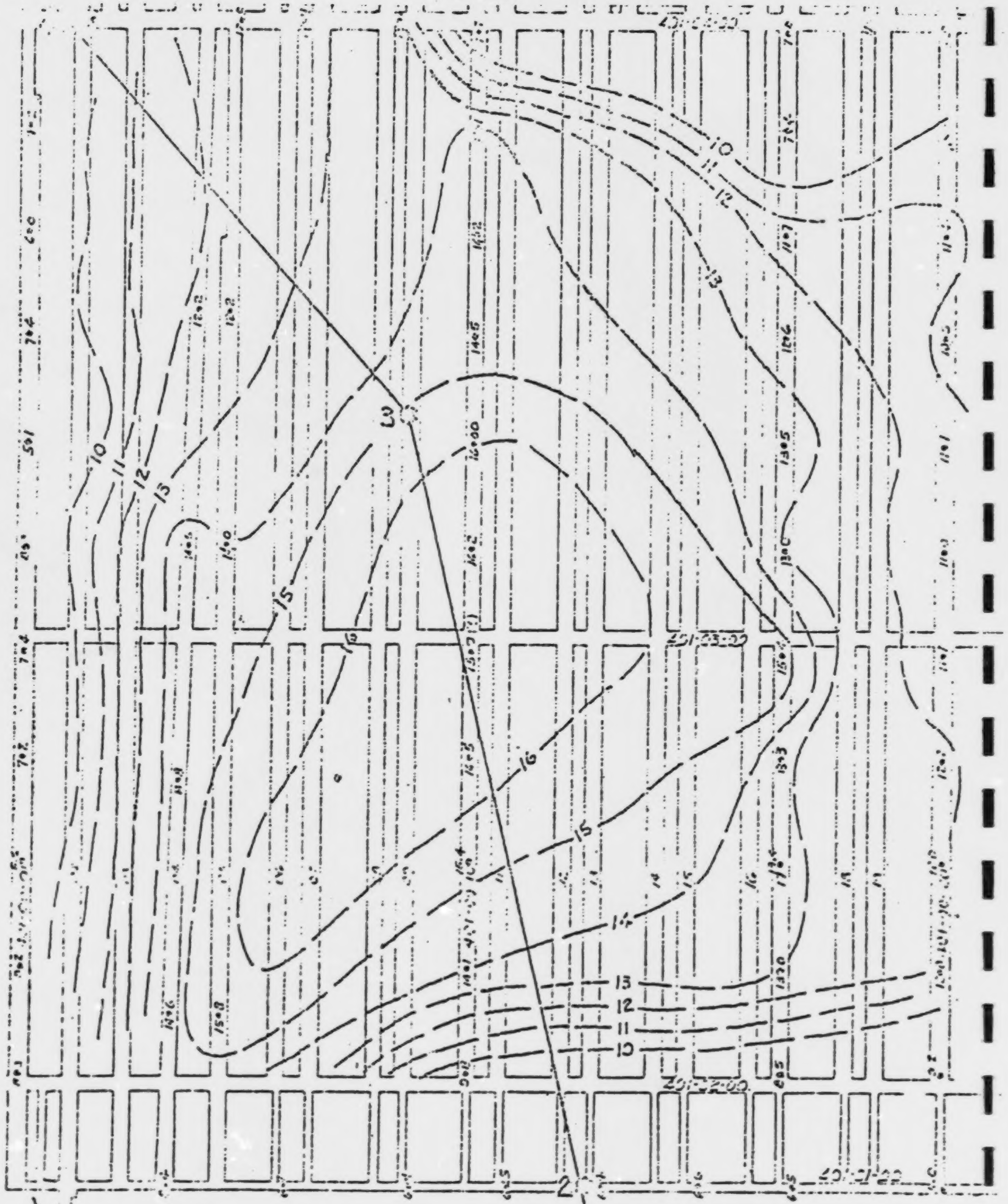


Fig. 7 - 21: (LOPEZ, 1977)

width of four passes.

Apparently, these larger pillars are much more effective in reducing the total closure, as indicated by the 10 - 12 in. contour lines which run approximately parallel to the block entry system towards the protective pillar of the main entry system.

The 10 - 12 in. contours also run nearly parallel to the block boundary against virgin ground.

In March 1976, 4 panels of block 3 had been extracted. As a result, the 10 - 12 in. contour lines run also approximately parallel to the temporary virgin ground boundary against block 3 until they turn into the mined-out area of block 3.

For the purpose of creating a 50-ft. pillar near block 3, the fourth room was cut converging towards the fifth room; the width of the third pillar increased correspondingly, see Fig. 7-21; this may have had a temporary effect until the extraction of block 3 started. However, the greater support provided by the wider pillar is still indicated by the greater distance between the 11 in. and the 12 in. contours near block 3.

The fact that the closure contour lines show "closure to be highest at the center" of the block, as LOPEZ (1977) put it, cannot be questioned. Figure 7-20 shows the same. The maximum closure in the central area of block 1 exceeded 16 inches (40.6 cm) in March 1976, indicating fully reloaded pillars.

C. Surface subsidence data.

It is of particular interest to compare the underground closure contours with the surface subsidences measured along the observation line 2-3-4 indicated on Fig. 7-21.

The measured surface subsidences are shown in Fig. 7-22. The observation line was installed in October 1972; the first measurements are assumed to represent the datum line of zero subsidence.

For reasons to be given in the following discussion, this writer cannot fully agree with the interpretation of the measurement data presented by LOPEZ (1977) with reference to SERATA (1976, Rock Mechanics Study for Sylvite, not published).

The following points are to be stressed:

1) In October 1972, benchmark 2, located above the boundary of

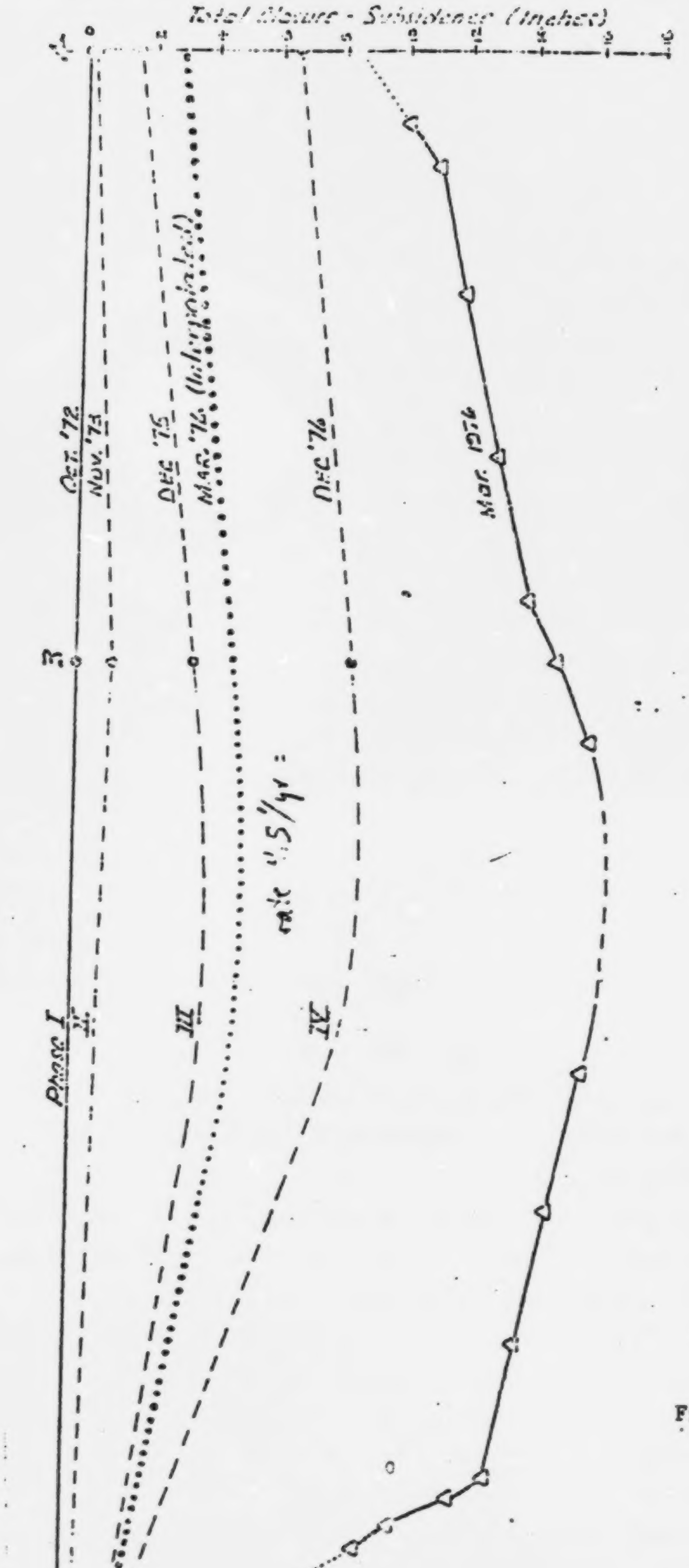


FIG. 13 SURFACE SUBSIDENCE AND PANEL AQ!
TOTAL ROOM CLOSURE (SECTION A-A)

Fig. 7 - 22: (LOPEZ, 1977)

block 1, had sufficient distance from the approaching retreat mining front to justify the assumption of zero subsidence; after cutting the first five rooms, the extraction of block 1 was temporarily halted, see Fig. 7-19. The horizontal distance between benchmark 2 and the projected extraction front was approximately 1500 ft. (457 m).

However, benchmark 3 is located at the projected distance of only approximately 650 ft. (195 m) from the experimental area in which one room was cut converging to the adjacent room to create a 50 ft. (15.2 m) pillar. Considering the fast reaction of the overburden which becomes apparent from Fig. 7-22, one could argue that the area of benchmark 3 was already affected in October 1972 as the experimental area with the 50-ft. 'yield' pillar was cut in July-August 1972.

In other words: benchmark 3 may not have recorded all of the subsidence which occurred at its location; however, the missing amount, if any, would be very small, as suggested by the subsidence measured from October 1972 to November 1973, see Fig. 7-22.

Benchmark 4, located at the corner of block 1, may indicate the full subsidence of that area, although the underground closure profiles of Fig. 7-19 could be used to argue differently.

2) The November 1973 subsidence profile of Fig. 7-22 was measured at the time when the projected retreat mining front reached benchmark 2, after passing over benchmark 3.

The closure profiles of Fig. 7-19 suggest maximum surface subsidence in the central area of block 1 rather than at benchmark 3 as shown in Fig. 7-22.

Benchmark 4 shows hardly any measured surface subsidence in November 1973. This writer's interpretation is based on the extraordinary width of the third pillar created by the 'converging' room, as already stressed in the preceding discussion of the closure contour lines, of Fig. 7-21.

3) The December 1976 surface subsidence profile was measured 1-1/2 years after the extraction of block 1 had been terminated.

In this writer's opinion the assumed delay in surface subsidence near benchmark 2, as shown in Fig. 7-22 cannot be justified. The surface subsidence profile should reflect the underground closure profile of March 1976 which is also shown in Fig. 7-22.

4) Regarding the closure profile of Fig. 7-22, an apparent error must be disregarded: the distances of the closure contours of Fig. 7-21 from the projected location of benchmark 2 are plotted incorrectly; apparently, the plotted distances refer to the inner edge of the two-entry block development system.

For reasons given previously, there is no basis for the comparison of the underground convergences in the entry system which reflect mainly stress relief creep and the surface subsidence measured at benchmark 2. Therefore, the dotted connection of the convergence profile with the projected location of benchmark 2 makes no sense, even if the actual opening convergence underneath benchmark 2 was indeed approximately 5 inches (12.7 cm).

For similar reasons, the three convergence values plotted next to the projected location of benchmark 4 must not be compared with convergences measured in the area of panel-and-pillar extraction of block 1. In addition, the subsidence of benchmark 4 was affected by the extraction of block 3, as shown previously.

5) For unexplained reasons, the 14 in. closure contour line of Fig. 7-21 is shown close to the projected benchmark 3. Unless the anomalous course of the contour line is explained, the data should not be used in comparisons of underground convergences and surface subsidences.

The same criticism applies to the 13 in. closure contour line in the same area. Apparently, the anomalous course of these two contour lines near the 'converging' pillar is caused by stress relief creep effects when the second room was cut. This is the reason why stress relief closures must not be used in assessing relationships between underground convergence and surface subsidence.

Furthermore, the experimental excavation of a three-room panel in block 3, see Fig. 7-18, in all probability resulted in heavy reloading of surrounding areas.

For these reasons, the course of the two contour lines after the excavation of the three-room panel should be different. The 14 in. contour line should not come as close to the 13 in. line as shown. The 13 in. contour line should be closed within block 1 rather than be shown running into block 3.

6) Figure 7-22 shows subsidences of approximately 4.5 in. (11.4 cm)

from December 1975 to December 1976 for benchmarks 3 and 4.

The closures in 1975 shown in Fig. 7-19 throughout block 1 are less than 2 in. (5.1 cm), i.e., the underground roof subsidence may be less than 1 in. (2.54 cm). Apparently, such measured surface subsidences and underground closures cannot be correlated without the assumption of rapid initial stress relief creep which does not necessarily result in surface subsidence. The process of overburden subsidence is working its way up to the surface over periods of time which depend on the mining sequence, and on the rate of lateral creep out of zones above and below barrier pillars.

It is shown in I/4.2.2, specifically in Fig. I/4-6, that the initial vertical extent of stress relief creep zones is reduced when effective overburden subsidence is initiated. This phenomenon may explain why the 1976 subsidence rate apparent from Fig. 7-22 is relatively high; it should decrease to become commensurate with the underground convergence rate after full pillar reloading with the deadweight of the overburden.

If the subsidence profile of benchmarks 3 and 4 for 1976 is based on correct data, the surface subsidence rate calculates as 4.5 in/yr (11.4 cm/yr), comparing well with the rates listed in Table 7-II.

7) It is interesting to calculate the time to complete closure of the rooms in block 1. The original height of the openings is 96 in. (244 cm). Allowing 16 in. (40.6 cm) for initial stress relief convergence, and taking 2 in. (5.1 cm) as the constant closure rate after full reloading of the barrier pillars, the time to complete closure of block 1 calculates as 40 years - about 10 years longer than for the first mined-out room-and-pillar block at the neighboring IMC mine, see I/5.2.1, Figs. I/5-1 and I/5-2.

However, it is stressed that the constant convergence rate after the extraction of a block must be determined carefully to make such calculations meaningful. Convergence rates measured at or near intersections must not be used as they are smaller than the rates at distances sufficient to eliminate the intersection effect. Anomalous convergence rates due to different room and pillar widths also must not be used.

As the constant final convergence rates commensurate with these conditions are not available for block 1, the exact time to complete closure of the mined-out block cannot be calculated. However, it is apparent that the panel-and-pillar layout with 50-ft. 'yield' pillars and 180-ft. barrier pillars results in closure and surface subsidence rates which are smaller than those observed at IMC in the first room-and-pillar block with 52-ft. pillars.

The most important conclusions to be drawn from the data published by LOPEZ (1977) are re-emphasized: it is not possible to design a stable mine at the depth given at PCS Rocanville (Sylvite). Constant convergence rates develop after extraction mining at reasonable extraction rates. These underground creep deformations control the subsidence of the overburden and result in constant surface subsidence rates. The limiting surface subsidence, and the time required to reach it, cannot be calculated exactly due to the lack of reliable data. However, the overburden apparently responds without delay to the extraction of large areas of the potash bed. Provided that the overburden subsidence is not disturbed by large remnants and false extraction sequences, there is no hazard of rockbursts due to delayed overburden subsidence caused by bridging overburden formations.

7.3 SECONDARY PILLAR EXTRACTION

7.3.1 General remarks

In potash mines with limited ore reserves, the extraction of the pillars left in the first cycle of room-and-pillar or panel-and-pillar mining is of great economic interest for apparent reasons: frequently, only up to 50% of the total ore reserves can be extracted in the first cycle of mining; the extraction of the remaining reserves requires no major investments.

Designers who theorize that stable mines must be developed by designing pillars as permanent stable support elements, and that overburden subsidence should be prevented because of the anticipated risk of groundwater inflow into the mines, tend to postpone the so-called second mining of pillars until the ore reserves recoverable by "safe" extraction methods are exhausted. This philosophy has no valid justification, particularly in mining potash beds of limited thickness. Overburden subsidence controlled by appropriate mine design is harmless, provided the impermeability of protecting salt strata above and below extracted potash beds can be maintained. In general, the chances of achieving this goal improve with increasing depths below surface, as shown in I/3.6.

Practical experience in several potash mining districts confirms these statements. As a matter of fact, even the total extraction of potash beds in one single step is known for decades to be feasible, as shown in 7.4.

Published surface subsidence data are extremely scarce; for unknown reasons companies and individuals who possess surface subsidence data to show the feasibility of second pillar mining appear reluctant to release detailed information. This is the reason why only a few case histories can be presented; the lack of detailed mine development data disallows any generalization of these case histories.

7.3.2 Carslbad potash mining district, New Mexico, U.S.A.

The successful application of second pillar mining in the Carlsbad district led to intensive studies by German writers when unexpected events during the early 1950's forced theoreticians to reconsider their hypotheses. The following descriptions are based on publications by STORCK (1962) and by GIMM (1968). The latter writer summarizes his studies as follows: In the Carlsbad district, room-and-pillar mining with long pillars as used in Germany began in 1931; soon thereafter standard room-and-pillar mining was introduced. Starting in 1948, attempts were made to improve the extraction ratio by extracting the pillars (second pillar mining).

The resulting uniform subsidence of the overburden did not cause any rock mechanical problems or water inflows.

Second pillar mining with planned overburden subsidence is now in general use. In the first mining cycle, standard room-and-pillar patterns are developed. In the second cycle, the pillars are extracted, leaving small remnants which account for losses of only 6 - 10% of the potash beds, see Fig. 7-23 (GIMM, 1968; the plan is also shown in a number of other publications).

Regarding the rock mechanical aspects of the first mining cycle, GIMM (l.c., pp. 373/374) re-emphasizes that modern room-and-pillar mining was first introduced in the Carlsbad district. In his opinion,

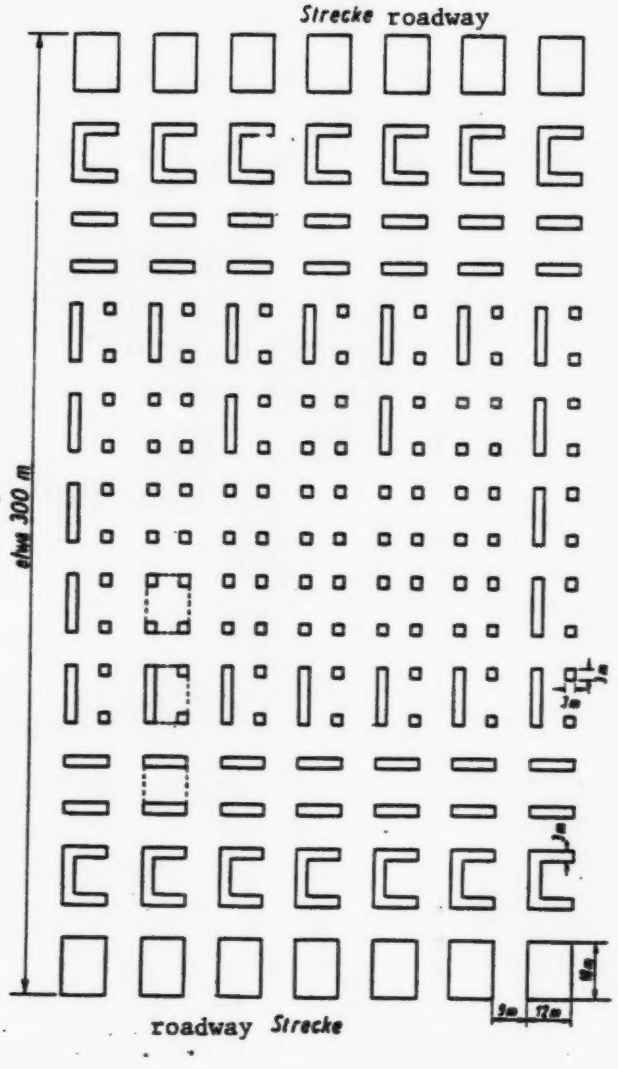


Fig. 7 - 23: Second pillar mining, Carlsbad, NM.
(GIMM, 1968)

the supporting capacity of square pillars is better than that of short pillars with rectangular sections; pillars with rhomoidal sections are considered most unfavorable.

Room and pillar dimensions and panel dimensions at depths of 300 - 400 m are given as follows: the pillar dimensions are 12 x 20 m up to 20 x 20 m; the panels may be square or rectangular, with spans of 200 - 300 m. The development entries are 8 - 12 m wide; the entry systems are protected by safety pillars (no dimensions given).

The writer expects that similar layouts will be introduced in all flat-lying potash beds to be extracted with modern equipment.

It may be stressed here that indeed standard room-and-pillar layouts were used in the first designs of most Canadian potash mines; for various reasons; these layouts were replaced by long-pillar layouts.

GIMM (1968, pp. 382/383) considers the second pillar mining in the Carlsbad district as "an ideal mining method in flat-lying potash beds with small to medium thicknesses" because this method does not intend to keep the overburden in its original position. Although this had been known for decades the SPACKELER/GIMM school kept postulating that stable mine design is necessary to prevent any overburden subsidence, see 7.2.1.

It is acknowledged that GIMM (1969) began to realize the significance of controlled overburden subsidence and to support this writer's views presented in a paper the publication of which had been suppressed in 1954, see BAAR (1959a, p. 250, introduction by the editor).

GIMM (1968, pp. 382/383) presents the following details of the second mining in the Carlsbad district: the sylvinite beds at depths from 260 m to 450 m are embedded in a rocksalt series approximately 100 to 150 m thick. In addition, a clay-marl bed 30 - 40 m thick covers the salt sequence and protects the mines against water inflows.

The plan of a mined-out panel, Fig. 7-23, is repeatedly shown in several publications.

The writer stresses that the second mining leaves pillar remnants of various dimensions. Usually there is a "soft transition" to entry systems: the first row of pillars along entry systems are left untouched, and the pillar dimensions decrease to 3-m square remnants in the central area of the panel. The writer emphasizes different time lags between first and second mining: some are waiting over ten years, some are starting the second mining immediately after the first room-and-pillar mining.

The underground subsidence caused by the second pillar extraction is described as follows: 20-40 m behind the second mining front, the destruction of the pillar remnants begins; at the distance of approximately 200 m from large pillars and/or virgin ground, roof and floor of the panels are in direct contact.

Due to the great convergences in the panels, corresponding surface subsidences are inevitable - up to 1.20 m were measured at the time when the report was written (no reference). The writer emphasizes the smooth development of surface subsidence troughs, although surface fractures may appear.

The writer also emphasizes that second mining is done in cases where two potash beds are extracted. First, the two beds are partially extracted in standard room-and-pillar patterns; subsequently, second pillar mining is done at the upper level; the lower level is nearly completely extracted after contact of roof and floor is established at the upper level.

GIMM (1959) presents differing descriptions with reference to unpublished reports by FOX/STORCK. The latter writer (STORCK, 1962) presents data which also differs to some extent from those reported above.

STORCK (1962, pp. 350-351) considers the extraction ratio of 90-95% achieved at the Southwest Potash Corporation mine as an example of near-perfect extraction of a potash bed at the depth of approximately 300 m. The sylvinite bed with the thickness of 1.65 - 1.80 m has a salt cover of 120 m.

In the first mining cycle, square pillars 20 x 20 m are left between rooms 12 m wide, resulting in an extraction ratio of 60¢. The second mining begins at the lease boundary; the pillars are reduced in size to approximately 4 m^2. The retreat mining front of 300 m length advances at the average daily rate of 1.80 - 2.40 m. The principal purpose of the pillar remnants is to provide safe roof conditions during retreat mining.

The first 300 - 450 m of retreat mining are considered particularly critical because the pillar remnants are not crushed completely; the roof strata transfer overburden load to the retreat mining front. In an umbrella zone 180 - 240 m wide along the lease boundary, the pillar remnants are not completely destroyed because of plate-like behavior of roof strata.

The writer assumes that this example of successful retreat mining encouraged other mining companies to begin similar retreat mining in 1961. In some contrast, GIMM (1958, p. 28) reports the International Minerals and Chemical Corporation as the first company to introduce second mining at the depth of approximately 400 m in 1948.

Some data given by the latter writer are emphasized because they reveal subsidence characteristics which appear to be typical of the Carlsbad potash mining district. Regrettably, the author fails to provide time data regarding the second pillar mining and the subsidence measurements. The location of the maximum surface settlement of 121 cm and the angle of draw of 36° at one side of the profile compared to only 22° at the other side indicate the direction of the second mining. Apparently, the surface subsidence measurements were taken shortly after the termination of the second mining; the subsidence trough is not yet fully developed near the profile end with the angle of draw of 22°.

Taking the maximum thickness of the potash bed of 180 cm, and the maximum depth of the surface subsidence trough of 121 cm, a calculation shows that approximately 67% of the possible underground subsidence at this location show already at the surface. This means that the limiting subsidence may have been reached but is continuing at the other end.

The fast reaction of the overburden to the complete removal of support cannot be considered as exceptional in view of similar fast reactions in other potash mining districts, as shown previously for cases where the exact dates of mining and surface subsidence measurements are known.

Considering such fast reactions of the overburden above a 120-m salt cover, this writer cannot agree with the assumption of an umbrella zone remaining effective over extended periods of time along the boundaries of mined-out areas.

This assumption is based on the erroneous postulate of elastic behavior of a 100-m rocksalt plate as temporarily promoted by HÖFER

(1958c), and explicitly supported by SPACKELER et al. (1960) and by STORCK (1962).

Stress concentrations near advancing and stationary total extraction fronts may develop and persist in coal mines; in salt and potash mines covered by 100 m of rocksalt, persistent stress concentration are not possible because of the creep behavior of salt rocks. The in-situ creep data presented in I/4 and I/5 provide ample proof of these relationships.

Needless to say that measurements to prove open voids along the boundaries of completely extracted areas are not available; observations cannot be made. However, the fact of complete closure of openings in salt rocks in time is established by measurements and observations. There is no reason for the assumption of different behavior of salt rocks in the Carlsbad district.

7.3.3 Partial pillar extraction, Werra potash mining district, Germany

GIMM (1968, pp. 372/373) describes two methods of secondary mining of long pillars in German potash mines at shallow depths:

1) the so-called pillar splitting, meaning that the widths of long pillars in mined-out areas are reduced from approximately 10 m to 5 m;
2) The so-called pillar cross-mining, meaning that long pillars in mined-out areas are partly extracted in long cross-rooms, leaving small square or rectangular pillars which are to be embedded in backfill. Subsidence data to show the effects of such pillar cross-mining are not available. However, other negative effects are shown in Chapter 2.

The writer makes no reference to a publication (HÖFER et al., 1967) with detailed descriptions of methods of secondary pillar extraction. The writers claim merit for having developed these methods on the basis of research by HÖFER (1958a, b).

The writers (l.c., p. 384) provide the following details and conditions for pillar splitting in several potash mines of the Werra potash mining district since 1963. The areas had been extracted up to several decades earlier using long-pillar layouts. The writers claim that up to 25% of the monthly production of some mines was obtained in splitting panels developed according to unpublished proposals by HÖFER (1962 and DUCHROW (1964).

Splitting panels were selected to suit the following conditions:

a) the potash bed must be sylvinitic ("Hartsalz");
b) the thickness must not exceed 3m;
c) the potash bed must be flat-lying;
d) no tectonic anomalies must exist in splitting panels;
e) the roof conditions must be good;
f) the splitting panel must be located outside of areas of potential water inflow;
g) the depth must not exceed 400 m;
h) the dimensions of any panel must not exceed 300 x 300 m;
i) the potash bed must have an above average K_2O content;
j) haulage must be inexpensive.

Most of these conditions apply to areas extracted during the first decades of potash mining in the Werra district.

The selection criteria, particularly h), indicate the expectation that no surface subsidence would occur according to hypotheses held at that time by SPACKELER et al. (1960): the 100-m rocksalt sequence above isolated splitting panels was expected to behave like an elastic plate; the remaining small pillars would provide some support for the bridging overburden. Abutments provided by large pillars in surrounding mined-out areas would carry most of the load.

Apparently, these hypotheses had to be changed when first results of measurements of surface subsidence above and trasnverse pillar expansion in splitting panels indicated continuing deformations. HÖFER et al. (l.c., p. 385) explain: "the increase in theoretical pillar loads from 225 ro 410 kp/cm^2, for example, resulted in pillar creep as the limit of elastic pillar behavior eas exceeded".

However, the writers (l.c., p. 386) expect strain-hardening of the pillar material due to creep; provided that the pillar remnants are adequately dimensioned and the size of any splitting panel is limited to the dimensions given under h) above, the deformations are expected to cease completely.

The writers assume relationships between overburden subsidence and pillar transverse expansion according to HÖFER (1958a). However the stress arch hypothesis is definitely dropped in view of the following measurements, including transverse pillar expansion upon pillar splitting, underground subsidence in splitting panels, and surface subsidence.

TABLE 7-VII

Examples of "pillar-splitting", Werra district, East Germany

No.	Depth (m)	Panel dimensions (m)	Area $(m)^2$	Average pillar height (m)
1	330	220 x 170	= 37400	2.9
2	340	300 x 240	= 72000	3.2
3	360	270 x 330	= 89100	2.9

The writers refer to an unpublished report and provide data on 3 panels with comparable geological conditions (see Table 7-VII). The writers (l.c., p. 385) emphasize that the underground subsidence increased considerably when the width of 3 neighboring pillars was reduced from 10 to 5.5 m and the span of the splitting panel reached just over 100 m.

The development of underground and surface subsidences troughs above the splitting panel is shown in Fig. 7-24.

The writers fail to indicate the extraction sequence, emphasizing the maximum underground subsidence at point 37 near the center of the second mining panel. However, the development of the underground subsidence profiles clearly shows the extraction sequence from point 47 to point 59 as the subsidences at points 47 - 45 are much greater than those measured at the opposite end of the profiles.

The same holds true for the corresponding surface subsidence profiles. The surface subsidence was surveyed since September 1963, while the underground measurements began in January 1964. An apparent error in Fig. 7-24 is to be corrected: the dates of both the surface and the underground subsidences correspond in both profiles, with the exception of the first profile in each series. For reasons given in the following discussion of pillar transverse expansions, the date of the first underground subsidence profile appears correct. The date of the first surface subsidence profile should be corrected accordingly.

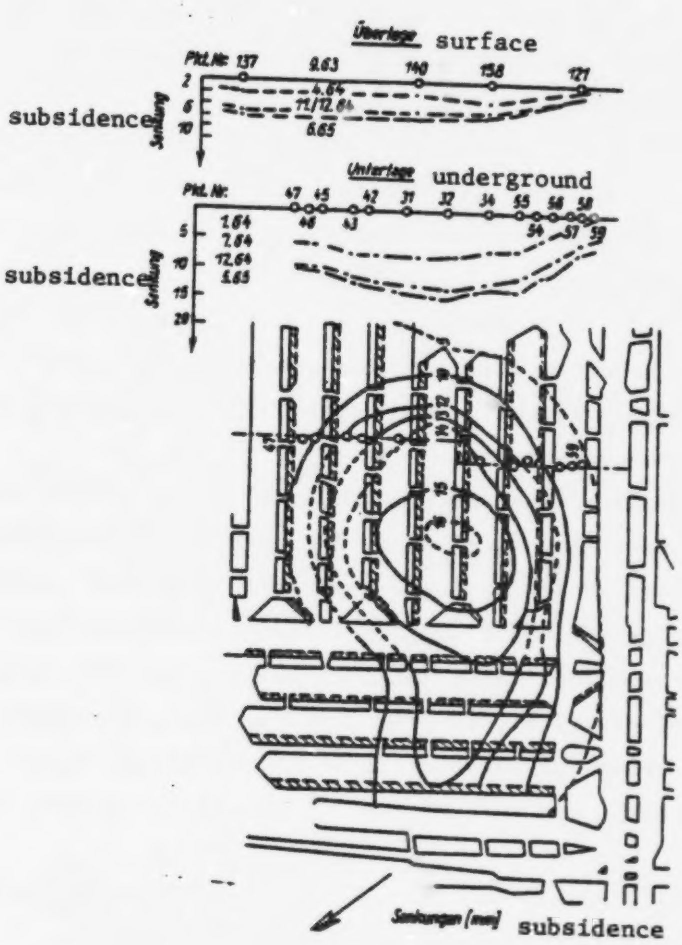


Fig. 7 - 24: Pillar splitting
"
(HOFER et al., 1967)

The writers (l.c., p. 385) are stressing the point that the zero contour line of the underground subsidence runs approximately 60 m outside the splitting panel through an old mined-out area which remained untouched. This statement is clearly contradicted by the first underground subsidence profile which shows zero subsidence at point 59 just inside the 5-mm contour line.

The only logical explanation appears to be that the second mining front arrived at the center of the splitting panel in July 1964, and that the pillar splitting started at point 47.

Emphasizing the smooth development of the subsidence troughs if the pillar splitting front advances uniformly, the writers (l.c., p. 386) state: the surface subsidences and the underground subsidences start at the same time; the surface subsidences correspond quantitatively to the underground subsidences. However according to Fig. 7-24, only 45% of the underground subsidences showed at the surface.

To prove their point, the writers present cumulative pillar expansion curves measured in 3 splitting panels, see Fig. 7-25. The exact locations of the measuring points are not shown; however the given lengths of measuring times make it possible to locate the points as follows on Fig. 7-24: point 1 near point 47, point 2 near point 54, and point 3 in the center of the adjacent splitting panel into which the underground subsidence contours extent, see Fig. 7-24.

The writers (l.c., p. 386) consider the curves shown in Fig. 7-25 as typical creep curves which indicate increasing pillar loads, depending on the depth and on the span of the splitting panel at any given time.

The parts A-B of the curves are considered indicative of slight pillar loading due to mining at distances up to 30 m.

The parts B-C are considered as the result of extraction near the measuring point, indicating almost instant loading of the remnants of splitted pillars.

The parts C-D, following the elastic deformation indicated by the preceding parts B-C, are thought to represent the transient creep of an ideal creep curve. The time of the subsequent change to constant creep rates cannot be determined exactly, according to the writers.

These interpretations cannot be accepted as the writers completely

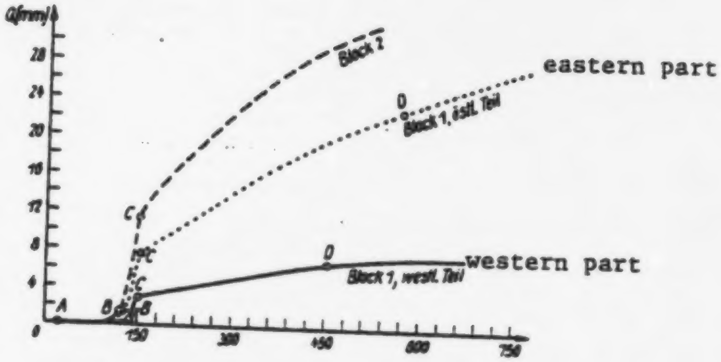


Fig. 7 - 25: Pillar expansion
(HÖFER et al., 1967)

ignore the effects of stress relief creep which results from decreasing the pillar widths from 10 m to 5.5 m and increasing the room width to 24.5 m. The writers also ignore the fact that stress relief creep takes place rapidly within hours or days when the width of a pillar is reduced.

However, the time requirements for creep deformation in the roof strata and for overburden subsidence to reach the surface are different. As these relationships are shown in detail in Chapter I/4 and I/5, and in the preceding sections of this Chapter, there appears no need for further discussion.

It is emphasized that the curves Fig. 7-25 reflect effects of stress relief creep and reloading creep as shown, for example, in Figs. I/5-1 to I/5-3 and Figs. 7-15 to 7-18.

As criticized previously, the writers terminated their measurements too soon, prior to obtaining constant final creep rates and corresponding surface subsidence rates. Their interpretation reflects hypotheses rather than the facts shown by the curves.

One final point may be emphasized: as the pillar creep curves shown in Fig. 7-25 reflect stress relief creep at least until sufficient spans of isolated splitting panels are reached, immediate surface subsidence must not be expected; the quoted relationship between underground and surface subsidences - 45% of the measured underground subsidences showed at the surface - clearly indicates that the limiting value of surface subsidence, see Fig. 7-1, was not reached at the end of the reported survey period.

7.3.4 Secondary pillar extraction after backfilling

This subject is covered in 7.2.1.1 with respect to surface subsidences caused by the extraction of pillars left between relatively high rooms which are backfilled with refinery waste.

The negative effects of using hot refinery waste for backfilling must be considered carefully, as shown in more detail in Chapters 2 and 3.

Under certain geological conditions, effective control of floor deformations is particularly important as shown in 7.2.1.1.

7.4 LONGWALL EXTRACTION OF POTASH BEDS

7.4.1 Roof control at the face

Various methods of longwall mining have been used for many decades to extract potash beds of limited thickness either completely or with relatively small losses. The potash mines of the Upper Rhine basin of France and Germany represent the best known examples dealt with in numerous publications in French and in German.

Safety against rock fall at the face, prior to intentional roof caving, is achieved either by artificial support such as self-advancing hydraulic support systems, or by pillar remnants which are blasted along predetermined caving lines.

Although apparent similarities with the longwall extraction of coal seams exist, there are important differences to be taken into consideration. Particularly the fast stress relief creep of saltrocks near advancing faces causes safety problems which are more serious in potash mines than in coal mines.

However, most writers ignore such effects of stress relief creep, theorizing that high abutment pressures are travelling at short distances ahead of advancing faces. Observed failures frequently are interpreted as caused by excessive loading, while in fact they are caused by excessive stress relief creep at and near advancing faces.

Reliable and detailed information is needed for the interpretation of the mechanisms of such failures; in most cases such information is not available.

Longwall extraction of potash beds has only local significance, and the following discussion is restricted to a few case histories of longwall extraction where measurement data were published.

7.4.2 Overburden control by intentional roof caving

7.4.2.1 Principles and prerequisites

The basic principle of overburden control by intentional roof caving is to take advantage of the increased volume of broken roof rock masses to the effect that the main overburden is safely supported at all times. Effective roof caving is to be achieved along predetermined caving lines.

The recompaction of the broken roof masses requires reloading by the subsiding main overburden. The process of subsidence above a developing longwall panel is working its way up to the surface. Finally, when certain spans of the mined-out have been reached, the caved rock masses at the extraction level are fully reloaded with the deadweight of the overburden.

Under certain geological conditions, control of floor deformations is the main purpose of intentional roof caving methods, as shown in detail in 8.2.

To make intentional roof caving feasible, geological prerequisites must be fulfilled, including:

1) The immediate roof strata of the extracted potash bed must break up easily at the designated caving line to minimum depths into the roof; these minimum depths depend on the thickness of the extracted potash bed and on the loosening factor *bulking factor) of the broken roof rock masses, i.e., on the ratio of the volumes of the roof rock before and after caving.

Relatively homogeneous salt sequences do not meet this condition. In some cases, blasting along caving lines is required to break down the rock salt beds for proper caving. Needless to say that the economics of intentional roof caving depend heavily on whether or not drilling and blasting is necessary.

2) No rigid formations must be present in the overburden as they would delay or disturb the process of overburden settlement onto the broken roof rock masses. Formations bridging across extracted areas cause heavy abutment loads until, at certain spans, sudden tensile failure may occur and result in sudden settlement of the overlying strata. This is the mechanism that causes severe rockbursts (earthquakes) as shown in detail in Chapter 2.

3) The effects of rapid stress relief creep upon the excavation itself, and upon roof caving, must be taken into careful consideration. In this regard, longwall extraction of potash beds differs to a great extent from longwall mining of coal seams. This is shown in the following re-interpretation of measurement data obtained at the Esparza mine, Potasas de Navarra, S.A., Spain.

7.4.2.2 Measurements, Esparza mine, Navarra, Spain

Published descriptions of the geology and the mining conditions at the Esparza mine difer considerably. The report by KRAMM (1971) appears to be the most comprehensive one; it is presented in the first place in literal translation. The writer refers to Fig. 7-26, indicating the locations of the refinery (F) and of the 5 shafts in the 100-km^2 lease between the two highways N 121 and N 111. The 2 Esparza shafts are inclined, the others are vertical.

"The deposit represents a W-E anticline; its section is listed in Table 7-VIII. According to what is known to date from exploration, the potash bed exhibits a very uniform composition over large areas and is dippling at 1 - 15° southwards. A few faults resulted in changes of 5 - 20 m in elevations of the potash beds; such changes can be absorbed in adequate mine planning."

"At the present time the 210-m sylvinite seam is being extracted; the extraction of the overlying 3.6-m carnallite seam is scheduled to start in the near future."

"The 100-m marl strata above the mines protect the potash beds against groundwater and allow the mechanized longwall extraction with intentional roof caving."

TABLE 7-VIII

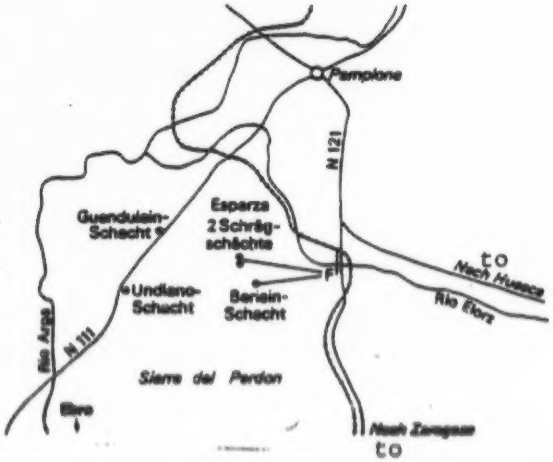
Geological section of the Esparza deposits (KRAMM, 1971)

Top:	5 m		sandstone with salt
	100 m		marl with gypsum
	3.5 m		carnallite, rocksalt, marl, beds alternating
	1 m		rocksalt
		1.7 m	carnallite
		0.2 m	rocksalt and marl
		1.7 m	carnallite
	0.7 m		rocksalt with little carnallite inclusions
		2.0 m	sylvinite, 20% K_2O, ore delivered to refinery 17% K_2O
	12 m		rocksalt
	1 m		anhydrite
	500 m		marl

NOTE: the section apparently applies to a location near the crest of the anticline where most of the sandstone was eroded, see Fig. 7-29.

Fig. 7 - 26: Esparza mine,
Navarra, Spain
Location map (KRAMM, 1971)

Schacht = shaft
Schrägschächte = inclined shafts



The writer provides some details regarding manpower, mining capacities, etc., of the two neighboring mining operations and continues: "The older mine shaft Beriain is 452 m deep...the new Esparza mine has two inclined access shafts 1100 m long...and the ventilation shaft Guendulain with the depth of 150 m...the ventilation shaft Undiano is under construction".

Fig. 7-27 shows the machinery used at the face of the seven panels required for the production of sufficient ore for the refinery; the face length is listed as 250 m. The extraction of the carnallite seam, scheduled to start late in 1970, should preceed the sylvinite extraction by 500 m. With the daily advance of 0.9 m of the face, the sylvinite seam would be extracted approximately 2 years later.

"It is expected that

1) after 2 years the overburden of the carnallite seam should have fully settled,
2) the rocksalt bed underneath the carnallite seam could serve as immediate roof for the extraction of the sylvinite seam".

OYANGUREN (1972, 1974) describes rock-mechanical investigations at the Esparza mine to determine the most suitable distance between carnallite and sylvinite faces. As his conclusions differ from those quoted above, quotations and literal translations, respectively, appear appropriate and are discussed after the presentation of Fig. 7-28 (WARDELL, 1968). The latter writer apparently also refers to the Esparza mine, postulating "an arch formation"; "thick, strong individual beds of rock in the overlying strata may be supposed to have influenced the structural behavior of the overlying rock mass. The idea of a so-called 'pressure arch' has, of course, been prevelant in the thinking of coal mining engineers for several decades".

With reference to 2.2.2, specifically Fig. 2-8, and in view of the span of only 125 m of the longwall panel "at a potash mine in Spain" at the depth of 200 m, there appears no need for further discussion of the postulated stress arch.

The quoted postulate is also shown premature by OYANGUREN (1972, 1974) on the basis of comprehensive measurements of the overburden reaction to the extraction of the sylvinite bed.

The writer (1974, p. 829) presents Fig. 7-29 as a typical geological

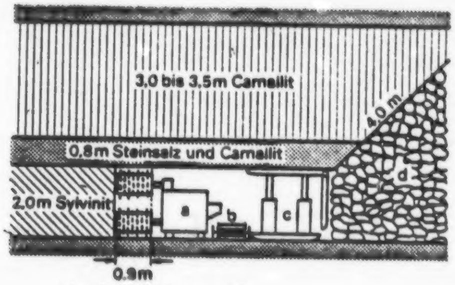


Fig. 7 - 27: Section at the longwall face (KRAMM, 1971)

Carnallit = carnallite

Steinsalz = rocksalt

a = Anderson-Boyes cutter
b = Westfalia belt
c = hydraulic support unit
d = drill and blast for roof caving

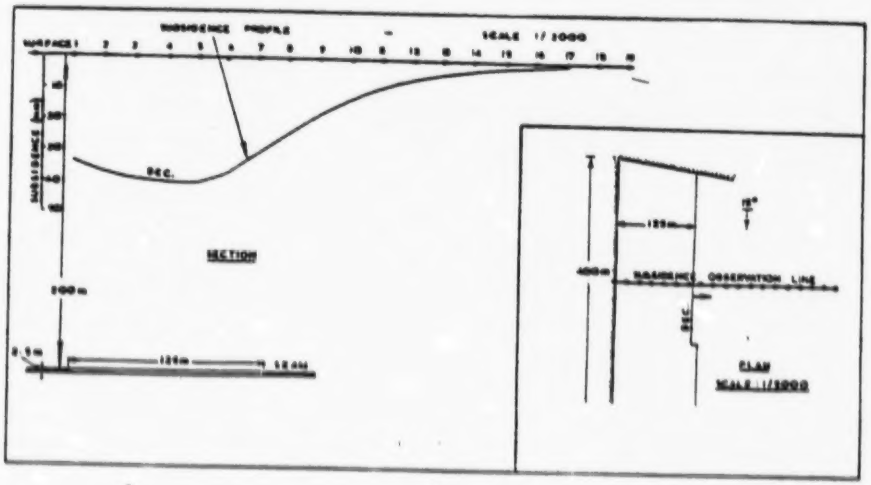


Fig. 7 - 28: Subsidence at a potash mine in Spain (WARDELL, 1968)

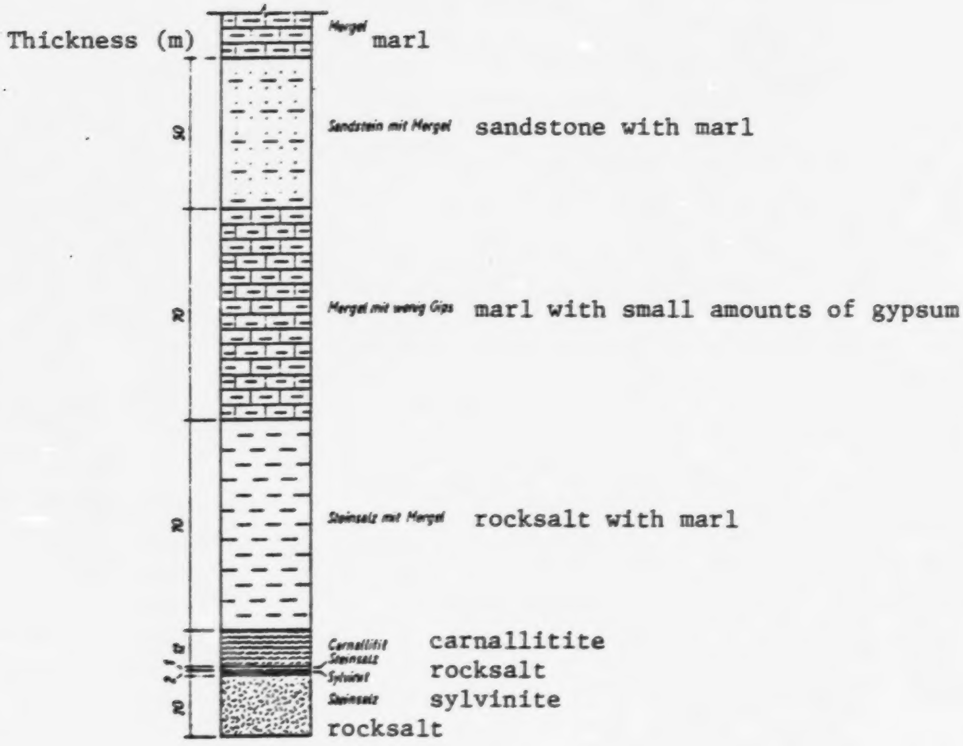


Fig. 7 - 29: Typical geological section, Esparza mine (OYANGUREN, 1974)

section. The 50-m sandstone series in the overburden is described as consisting of thick sandstone beds alternating with thin marl layers. The sandstone is outcropping at some locations, but in most areas of the lease it is covered by marl.

The sandstone is water-bearing; its permeability decreases rapidly with the distance from outcrops due to lack of weathering. The groundwater level in the sandstone shows no seasonal changes. The writer stresses the point that no extraction mining took place near the surface; the minimum vertical depths of mined-out areas are reported as approximately 160 m.

According to OYANGUREN (1974, p. 829), the effectiveness of the overburden in protecting the mine against groundwater inflow was in question when the first surface subsidence measurements showed abnormally little subsidence as seen in Fig. 7-28.

"It was known that too much of deformation underneath the sandstone would result in bed separation voids along which groundwater would flow into the mine workings". The sandstone, behaving like an elastic beam, would fail upon reaching a sufficient span.

For this reason, a comprehensive research program was initiated. Overburden subsidence measurements started in July 1965 above sylvinite panels and in March 1970 above carnallite panels.

The second purpose of the research program was to determine the minimum distance between carnallite faces and sylvinite faces. The carnallite seam would be extracted first, leaving the floor rocksalt bed untouched as shown in Fig. 7-27.

In contrast to the quoted expectations (KRAMM, 1971), OYANGUREN (1972) arrives at different views regarding the distance between carnallite and sylvinite faces after analyzing all the results obtained from the measurements: "we reach the conclusion that at a distance of about 0.9 times the depth of the panel behind the face, the ground above the excavation is nearly stabilized and the pressure on the goaf reaches the value of the overburden pressure. We think that this conclusion is relatively independent of the height of the seam. Therefore, the minimum distance between the carnallite and sylvinite faces on the longwall caving simultaneous extracting panels should be equal to 0.9 times the depth of the seam".

Referring to the questions raised on account of the subsidence data shown in Fig. 7-28, the writer (1974, p. 832) concludes: "it has been shown that there is not a formation present between surface and extraction panels which would store load or behave like a rigid beam, in which case sudden collapse of the overburden may eventually occur. The extraction of the sylvinite seam underneath mined-out carnallite panels is scheduled to start before the end of 1974".

It should be noticed that the writer refers to beam behavior of overburden strata; the stress arch hypotheses is not even mentioned.

The overburden subsidence measurements referred to in the above quotations are unique indeed, at least regarding salt and potash mining. For this reason, the measuring system and the results obtained are shown in the following discussion.

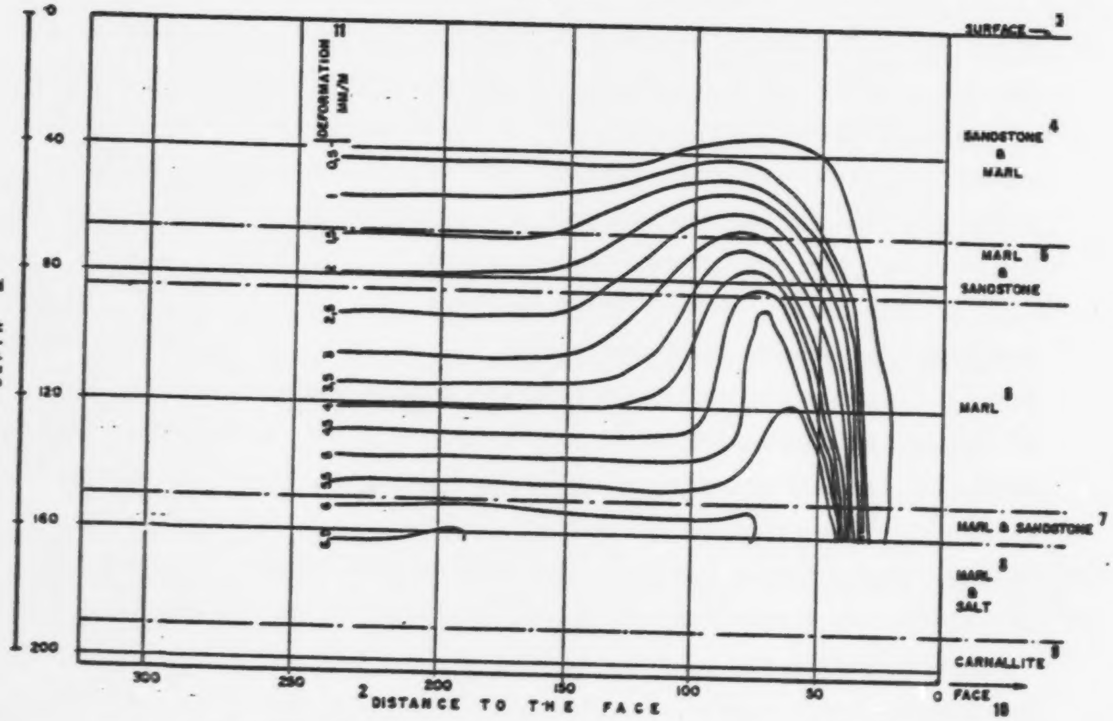
The contours of equal vertical ground deformation shown in Fig. 7-30 are calculated from measured settlements of "anchors set in boreholes drilled from the surface" (OYANGUREN, 1972, p. 1). The writer (1974, p. 830) describes the measuring system as follows, with reference to Fig. 7-29:

"Six boreholes were drilled from the surface to the marl-salt interface. 5 of these 6 holes were located above sylvinite extraction areas, 1 was located above an area of carnallite extraction. These holes were lined and cemented in the sandstone to seal them against water inflow."

"At the distance of 3 m from each of these deep holes, 6 holes were drilled to the bottom of the sandstone" (approximately 140 m above the top of the carnallite, 152 m above the top of the rocksalt bed above the sylvinite seam, see Fig. 7-29).

"Hydraulic borehole anchors approximately 10.2 cm in diameter were especially developed for these measurements. Above sylvinite panels 3 anchors were set in each of the deep boreholes: one at the bottom of the hole, 3-4 m underneath the marl-salt interface; the second one 3-4 m above the marl-salt interface, the third one at the sandstone-marl interface" (apparently at the bottom of the sandstone).

"In each of the additional holes drilled to the bottom of the sandstone, one anchor was set just above the sandstone-marl interface. In the borehole located above the area of carnallite extraction, three



Contours of Equal Vertical Ground Deformation. Fig. 7 - 30: (OYANGUREN, 1972) additional anchors were set: one 5 m above the deepest anchor at the sandstone-marl interface, the second one at the interface sandstone-upper marl, the third one 3-4 m above this interface in the upper marl. Above the area of carnallite extraction, the deepest anchor was set at the depth of approximately 300 m below surface."

"All anchors are connected with stainless stell wires to surface monuments above the boreholes; the extension between the monument and each anchor was measured at appropriate time intervals."

Similar instrumentation has been used extensively in deep potash mines for measurements of creep deformations around underground excavations, see Chapters I/4 and I/5. The changes in lengths between pairs of anchors, and between each anchor and a reference point outside the borehole, can be measured precisely and recorded continuously (BAAR, 1953a, c, 1954a). Such measurements contributed much to the understanding of underground creep deformations.

At this point, it must be emphasized: the calculation of average deformations between reference points (in mm per m of the total original distance between the reference points) may be misleading. In fact, if indeed bed separation takes place between a pair of reference points, such calculations are misleading because the total measured deformation, or any fraction of it, may be attributable to bed separation. Such separation voids may open when deformation occurs and close when it terminates, the process shifting to strata above the reference section.

Such opening and closing of separation voids may take place within relatively short periods of time which are comparable with the time periods between measurements of the subsidence above the Esparza mine. In one case history observed in a potash mine and documented by several photographs (BAAR, 1958), separation voids opened in an entry over approximately 100 m length to the maximum width of 30 cm, and closed subsequently when overlying strata began to subside. These observations are considered extremely significant in the interpretation of overburden subsidence above the Esparza mine.

Fig. 7-30 (OYANGUREN, 1972) "shows the contours of equal vertical ground deformation above" a sylvinite longwall face "at a depth of about 200 m. There it can be seen that at more or less 180 m behind the face the ground is nearly stabilized. These results were obtained by anchors set in boreholes drilled from the surface".

Fig. 7-31 refers to the same panel and shows "the subsidence of a roof layer located at a depth of 158 m" (compared with an "overburden pressure" curve based on questionable measurements to be discussed later).

In his 1974 publication, the writer apparently refers to the same measurements; according to the preceeding quotations, only 5 holes were drilled above a sylvinite extraction area. However, the data presented in the 1974 publication differ considerably from those shown in Figs. 7-30 and 7-31, so the following detailed discussion appears indicated.

Fig. 7-32 shows "the absolute vertical displacement of the surface and of 4 anchors set" at the indicated depths of 80, 95, 147, and 177 m; the depth of the extracted sylvinite seam is given as 210 m, the seam thickness as 1.9 m.

Fig. 7-31 shows the "maximum subsidence" at 158-m depth levelling off to 1500 mm; no further subsidence was measured after the distance to the face had reached approximately 160 m.

However, Fig. 7-32 shows the subsidence at 177 m depth levelling off to slightly more than 1700 mm at the distance of 350 m from the face.

As the writer fails to give any time data related to the measurements, an explanation of the differences in the two sets of curves cannot be given by this writer. However, some important conclusions not mentioned in the reference papers can be drawn:

Fig. 7-30 shows the maximum vertical deformation exceeding 6 mm/m between the top of the extracted sylvinite bed at the depth of 210 m and an anchor set at the depth of 158 m. According to these figures, the length of this 52-m section increased by 312 mm. The writer (1972, Fig. 2) shows very slow pressure increase behind another face at the depth of 400 m. Fig. 7-31 shows the same for the face at the depth of 200 or 210 m. This indicates that caving according to Fig. 7-27 did not extend deep into the roof rocksalt.

In all probability, an unknown fraction of the 312-mm roof subsidence near the face of the developing panel is attributable to stress relief creep.

The remaining fraction is attributable to lateral relief creep

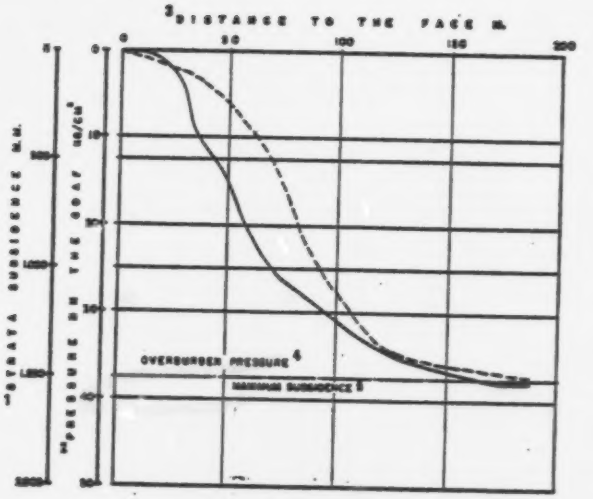


Fig. 7 - 31: Subsidence of a roof layer located at a depth of 158 m

(OYANGUREN, 1972)

Overburden pressure curve dashed

out of the abutment zone which travels ahead of the face.

Such lateral creep is known for causing bed separation voids in well-straitifed salt sequences, as shown in I/4 and I/5. There is reason to assume that bed separation voids near the advancing face are at least partly the cause of the deformation shown in Fig. 7-31 for the roof salt sequence.

There are more reasons for the assumption that separation voids opened temporarily in the overlying marl. Under the given conditions, rocks such as marl do not exhibit stress relief creep; however separation voids may open when the span of the extracted area increases.

The strongest argument in favor of temporary bed separation as the dominant feature in the subsidence process behind advancing faces is based on the following statement (OYANGUREN 1972, p. 3): "the pressure on the broken rock area...increases very slowly to reach the overburden pressure at a distance of 320 - 440 m behind the face (at the depth of 400 m). All the results...indicate that the rear of goaf abutment does not exit".

With reference to Fig. 7-31 the writer emphasizes the "good correlation between the vertical stress on the goaf and the subsidence of the roof strata near the seam. As we saw before, the ground movement above the excavation becomes negligible at a distance of about 180 m behind the face".

The latter statement is quantified as follows (1974, p. 830): "at the horizontal distance of 0.9 times the depth behind the face, the recompaction of the overburden is nearly completed; 90% of the total subsidence have already taken place."

It goes without saying that the recompaction of broken rock masses of great thicknesses, consisting of rocksalt and marl fragments of unknown size, requires considerable time and vertical force. However, such force apparently was not available according to the quoted statements. This leaves no alternative to the assumption that only a few metres of the immediate carnallite roof broke down upon blasting according to Fig. 7-27; the overlying strata performed the measured subsidence without any significant rupture.

Such behavior invites temporary bed separation due to varying bed thicknesses of the strata units involved. The closure of temporary separation voids does not require any vertical pressures; just bending with increasing spans is sufficient.

Vertical pressure to recompact the broken carnallite masses began to build up slowly at distances behind the face which are considerably greater than the distances at which roof subsidence occurred at the maximum rate, see Fig. 7-31. As carnallite is relatively easily deformable, the recompaction of broken carnallite masses does not require high abutment loads. The recompaction begins when bed separation voids in the immediate roof are closed.

In fact, the apparent lag between pressure build-up in the extracted area and roof subsidence seen in Fig. 7-31 can be considered as indicative of roof bed separations which had disappeared at the distance of approximately 120 m behind the advancing face.

These relationships are also demonstrated by the following figures which present the measurement data in different ways (OYANGUREN, 1974).

Fig. 7-32 shows the absolute vertical movements of anchors set at the indicated depths. The writer gives no comments on the development of the apparent subsidence troughs. The following points are stressed here:

1) There is very little surface subsidence above the advancing face. The surface subsidence trough extends only approximately 20 m ahead of the face; this means that the angle of draw, see Fig. 7-1, is nearly 90° - in quite some contrast to the surface subsidence troughs shown so far in this text. If the measurements are precise, they indicate that hardly any overburden load was transferred to the postulated abutment ahead of the face. Normally, an angle of draw of approximately 45° would be expected.

The explanation may be that the position of the face in Fig. 7-32 coincides with one of the faults reported by KRAMM (1971).

2) The anchor set at the depth of 177 m, 33 m above the extraction level of 210 m, is the first one to indicate the almost immediate reaction to the excavation, in contrast to the surface reference point. As the anchor is set in rocksalt underneath the salt-marl interface, its reaction is at least in part due to stress relief creep into the excavation at the advancing extraction front.

At distances exceeding 350 m from the extraction front, the sub-

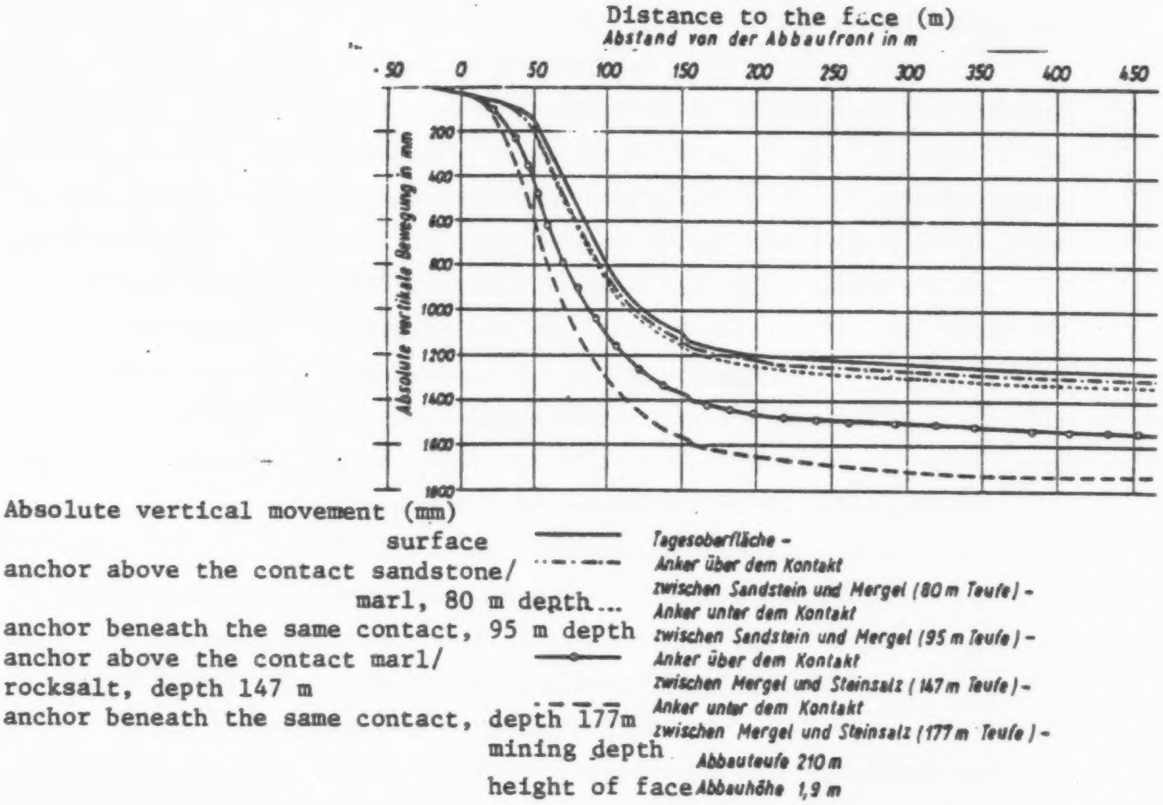


Fig. 7 - 32: Absolute vertical displacements (OYANGUREN, 1974)

sidence curve of this anchor is shown running parallel to the bottom reference line, indicating the termination of all deformation processes near the extraction level, including the recompression of stress relief creep zones, the closure of possible bed separation voids, and the recompaction of broken rock masses. The subsidence of this anchor reached approximately 1.75 m of the maximum possible 1.9 m (thickness of the extracted sylvinite bed).

The height of the excavation was increased to an unknown effective height by intentional roof caving; this makes rapid lateral stress relief creep of the carnallite possible. The remaining vertical deformation of the 33-m roof section - 0.15 m - also appears mainly attributable to lateral stress relief creep.

The reader is referred to I/4.2.2. OYANGUREN (1972, p. 2) stresses the point that the abutment load near the advancing face "reaches a maximum equal to about twice the cover load". Such abutment loads cause more initial lateral stress relief creep of the easily deforming carnallite.

3) Fig. 7-32 shows the choice of the value "180 m behind the face, 0.9 times the depth," rather arbitrary and probably due to an error.

The deformation rates decrease regularly, indicating the increasing resistance against recompaction of the caved roof rock masses.

All curves of Fig. 7-32 show an irregularity at the distance of 150 m behind the face. The writer provides no explanation.

The fact that the irregularity shows first at the surface, and correspondingly later in all other curves, could support the assumption that a fracture formed near the surface as observed on the occasion of rockbursts, see Chapter 2.

Another possible interpretation might be that the developing surface subsidence trough reached a pre-existing fault.

At the distance of 180 m from the face, all curves of Fig. 7-32 begin to show the slow but constant deepening of the subsidence troughs. There is no justification for selecting the distance of 180 m as the distance at which "the ground is nearly stabilized", or at which "the ground movement above the excavation becomes negligible."

4) One curve of Fig. 7-32 shows the movement of the anchor set above the salt-marl interface at the depth of 147 m; it indicates the

vertical deformation of strata which are 30 m thick, and include the top salt strata above the anchor set at the depth of 177 m.

These two curves diverge more and more until the distance of 350 m from the face is reached; then the two curves converge indicating continuing recompaction.

5) Another pair of curves of Fig. 7-32 indicates the vertical deformation of the marl between the depths of 95 and 147 m (thickness 52 m). The curves diverge to the distance of 150 m, the irregularity discussed under 3) eliminated some delay in the subsidence of the overlying sandstone; then the curves are running virtually parallel, indicating the termination of any deformation in the marl. This development indicates that bed separation voids did not develop in the marl, but possibly at the lower marl-sandstone interface, being eliminated at the distance of 150 m from the face.

6) The surface subsidence curve runs virtually parallel to curves for the depths of 80 and 95 m. Apparently, very little vertical deformation took place in the sandstone and the overlying marl.

It is re-emphasized that all curves develop into straight lines with the same angle to a horizontal line, indicating continuing subsidence of all strata above the extraction level at a small, but constant rate.

Fig. 7-33 shows the absolute subsidence of Fig. 7-32 calculated as average vertical expansion in mm/m.

Curve 1 represents the average expansion "at the lower salt/marl interface at the depth of 162 m."

Curve 2 shows the average expansion "at the upper marl-sandstone interface at the depth of 121 m."

Curve 3 demonstrates very little expansion "in the sandstone at the depth of 40 m."

The curves confirm the sequence of vertical deformation in subsequent overburden sections as outlined above. It should be borne in mind that the horizontal scale refers to the development of the span of the excavation; as the average daily advance of the extraction front was 0.9 m, the horizontal scale also provides an approximate time scale. This is significant as the creep deformations of the salt rocks depend on time, while the deformations of the marl and

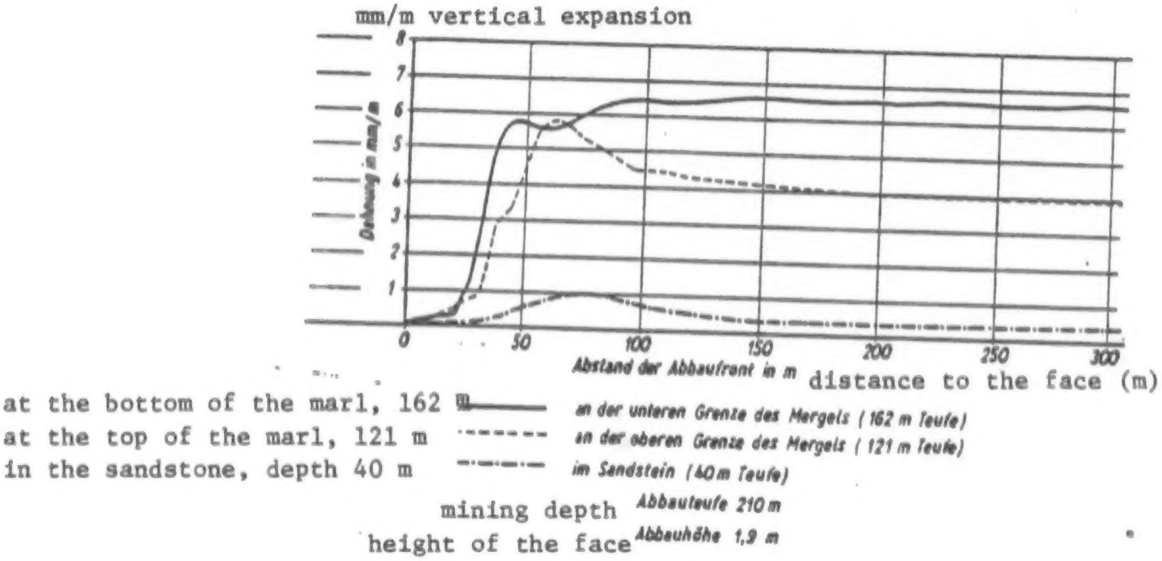


Fig. 7 - 33: Average vertical expansion at various depths (OYANGUREN, 1974)

sandstone strata depend on the span of the excavation.

Curve 1 is the first curve to show a sharp increase in deformation rates when the span of the extracted area exceeded 20 m. As outlined above under 2), the vertical expansion of the salt cover can in part be attributed to stress relief creep. However, the sharp increase which continued until the span reached 40 m appears to indicate bed separations in the salt cover.

Curve 2 shows the assumed bed separations extending into the overlying marl, following the increase in vertical deformation rates of the salt cover with a time lag of several days at the beginning. The time lag increases to several weeks. While the vertical deformation of the salt cover is shown discontinuing at the span of approximately 40 m, the deformation of the overlying marl continued until the span reached approximately 60 m. At this span, the average vertical deformation rate of the marl is shown just exceeding the average deformation rate of the salt cover.

This development is interpreted as follows: common source of all deformations is stress relief creep which results from the excavation of the sylvinite bed and is enhanced by the intentional caving of the roof carnallite. At the distance of about 20 m from the face, lateral stress relief creep started to cause roof bed separations.

At the span of 40 m, sagging roof salt beds came into contact with the caved rock masses; the vertical deformation of the salt cover is shown terminated; bed separation voids - if any - are beginning to close, as indicated by the slight decline of curve 1 between the spans of 40 and 60 m.

The constant rate of vertical deformation at distances exceeding 90 m should be noticed. As the horizontal creep of the salt rocks out of the abutment zone of the excavation continued, and the overlying marl does not exhibit stress relief creep, buckling of separating marl beds due to the lateral forces resulting from horizontal creep of the salt rocks is assumed as the cause of the continuing increase in the average deformation rate of the marl indicated by curve 2 up to the span of 60 m.

At the span of 40 - 50 m of the excavation, the sandstone formation began to exhibit slightly increased deformation rates as shown by the third curve of Fig. 7-33. The curve supports the previous statement that very little vertical deformation took place in the sandstone. Apparently, the sandstone and the overlying marl were bending as a whole, following the subsidence of the underlying strata.

Curve 2 of Fig. 7-33 demonstrates effects of the sandstone subsidence: when the span of the excavation exceeded 60 - 70 m, the average deformation rate of the underlying marl began to decrease. The decrease to the span of approximately 150 m appears to be attributable to the closure of bed separation voids in the marl.

The sequence of expansions and recompactions is re-emphasized: expansion began at the extraction level, working its way up to near-surface strata; recompaction began when near-surface strata began to subside, the reloading process working its way down to the extraction level. This sequence is clearly reflected in the curves of absolute subsidences shown in Fig. 7-32 as outlined previously.

The temporary increase in the vertical deformation rate of the salt cover as shown in Fig. 7-33 at spans of 70 - 90 m cannot be reconciled with the logical sequence of expansion and recompactio, unless it reflects the closure of bed separation voids. Another possibility might be that the temporary decline of curve 1 between the spans of 40 and 60 m may reflect small reading errors at the crucial points in time.

Furthermore, the sudden increase in absolute subsidences shown in Fig. 7-32 at the span of 150 m does not show at all in Fig. 7-33. However there can be no question as to increased overburden loads at all reference levels after the elimination of some obstacle to uniform overburden settlement at the span of 150 m.

It is re-emphasized that salt rocks, particularly carnallite, are easily recompacted as their creep into any voids left after intentional caving begins under relatively small loads provided by subsiding overburden. Such recompaction should have become measurable shortly after the span of 150 m was reached, if indeed the recompaction of the salt cover and the broken carnallite terminated at the span of 350 m as shown in Fig. 7-32.

It is difficult to attribute such minor inconsistencies in the figures presented by OYANGUREN (1972) to inaccuracies in measurements, to preconceived hypotheses developed in coal mining, or to oversimplifications in the preperation of the figures.

The assumption of abutment loads "equal to about twice the cover load" of 90 kp/cm^2 "at a distance of two or three metres in front of the face; this is the location of the front abutment" (l.c., p. 3) is definitely not acceptable. Such stress increases are assumed where and when "stress-meters" and extensometers indicate deformations as shown in detail in I/5.4.2 and I/4.4.2. The rapid initial stress relief creep of salt rocks must not be ignored.

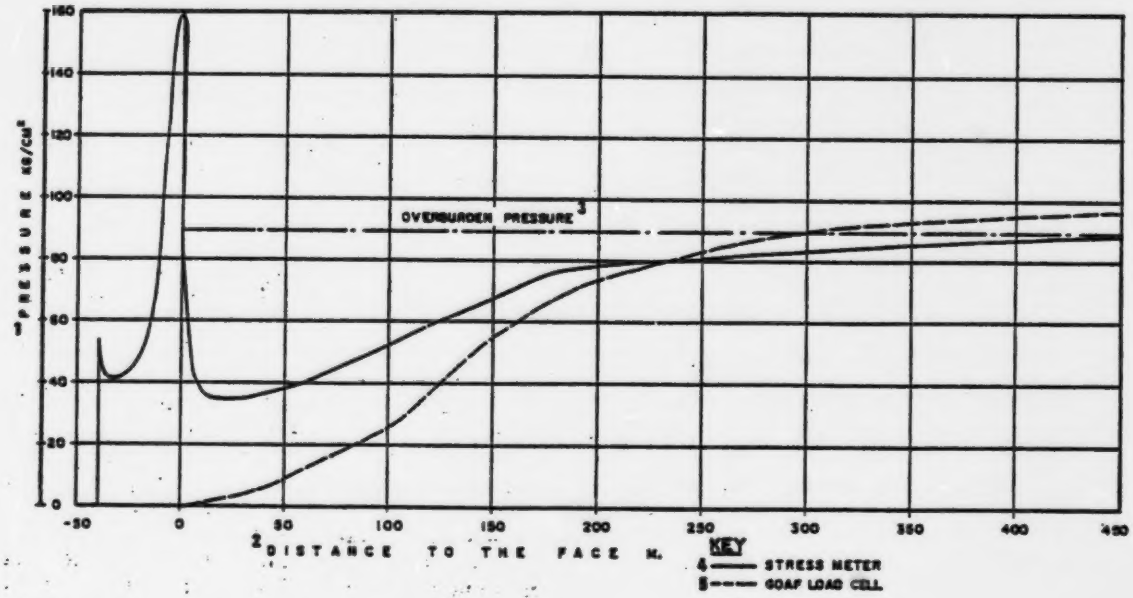
OYANGUREN (1972, p. 4) is trying to prove obsolete hypotheses by measurements of "the deformation of the strata close to the seam in front of and behind the face. These measurements have been performed at the present sylvinite faces...The horizontal tension deformation in the seam in front of the face can be seen" on a figure which is shown here as Fig. 7-34. "The measurements have been taken from a roadway driven into the bed parallel to the face using the strain wire borehole technique".

In fact, Fig. 7-34 demonstrates rates of stress relief creep into the excavation, extending to approximately 90 m after roof caving. The span of the approaching mined-out area is not indicated. However, the creep rate near the approaching face is rather high and demonstrates the presence of a wide front abutment zone into which the extraction front advances; the stress relief creep zone is travelling ahead of the face as shown in detail in I/5.5.2.

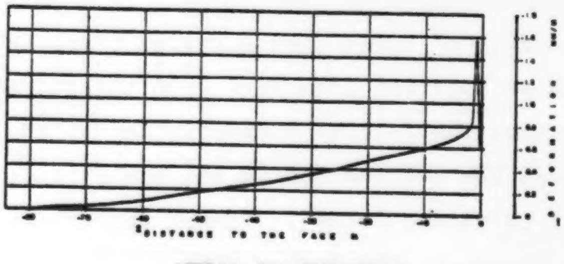
Taking the indicated value of 2 mm/m at the distance of 5 m from the approaching face, and considering the steep increase of the curve towards the face, one cannot escape the conclusion that considerably more stress relief creep occurred closer to the face. The reader is referred to Fig. I/5-12 which shows stress relief creep caused by excavations the height of which may be similar to the height of the extracted sylvinite bed plus the height of the caved roof, and to Figs. I/4-1 and I/4-14; when comparing the latter two figures, it should be borne in mind that some stress relief creep is missing in these figures.

On the other hand, the original overburden load is much higher in the case histories referred to. This difference may have been reduced by abutment loads of unknown magnitude in the case of Fig. 7-34.

In Fig. 7-35, OYANGUREN (1972, Fig. 6) presents his interpretation



Pressure Distribution Normal to the Face Depth 400 m. Fig. 7 - 34 (OYANGUREN, 1972)



VERTICAL BED DEFORMATION IN FRONT OF THE FACE

FIGURE-6

Vertical Bed Deformation in Front of the Face.

Fig. 7 - 35 (OYANGUREN, 1972)

of measurements taken in "a roadway parallel to the front driven into the rocksalt underneath the bed". Details are not given; the interpretation reads: "the front abutment which is about one metre inside the seam, is very sharply marked". The "vertical compressional strain in the seam" is shown jumping to 1.6 mm/m at 1 m distance from the face, falling to 0.8 mm/m at the distance of 2 m, and decreasing regularly to zero at the distance of 80 m.

This interpretation also ignores the rapid stress relief creep into any new excavation in salt rocks. Due to the lack of details, no reasons can be offered to support the statement that the interpretation appears untenable.

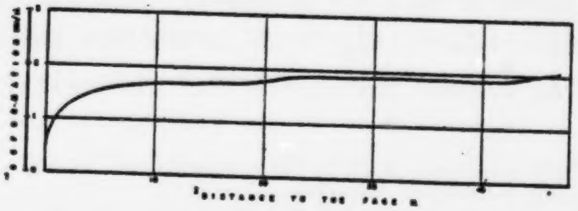
The effects of rapid stress relief creep behind advancing sylvinite faces are also apparent from Fig. 7-36 (OYANGUREN, 1972, Fig. 7). The writer provides the following description of the measurements: "we have measured the deformation in the rocksalt strata at the floor of the present sylvinite faces". "These measurements have been taken from a roadway underneath the bed". "The vertical tension strain in the floor is shown at a present sylvinite face between points at 0.2 and 1.6 m of depth from the floor. As can be seen most of the deformation takes place within 10 m behind the front".

The latter statement characterizes the measured deformations as typical stress relief creep deformations such as shown, for example, by Fig. I/405.

The reader is reminded of the earlier statement that the distances from the advancing face provide an approximate time scale.

Fig. 7-36 indicates some vertical floor deformation ahead of the advancing face, as is to be expected since stress relief creep takes place from all directions into an advancing excavation. This is shown in I/4.3.2, see Fig. I/4-7.

The increases in vertical deformation rates into the overlying excavation at distances of 20 and 45 m behind the face are remarkable; apparently, caved roof rock masses cannot cause an acceleration of continuing floor uplift. Increasing stress relief creep rates also cannot be assumed as the deformation curve had levelled off prior to taking the slight jumps at the indicated distances. Floor bed separation underneath the extracted area appears to be the only possible interpre-



FLOOR DEFORMATION AT THE GOAF
BETWEEN POINTS AT 0.2 AND 1.6 M. DEPTH

FIGURE- 7

Floor Deformation at the Goaf between Points at 0·2 and 1·6 m. Depth.

Fig. 7 - 36: (OYANGUREN, 1972)

tation.

Such bed separations are common in salt and potash mines, even in room-and-pillar mines, if the pillars are ineffective due to rapid stress relief creep, see I/5.3.2, particularly Figs. I/5-11 through I/5-13B. It might be possible that gas or brine pressures according to Fig. I/4-16 contributed to the assumed bed separations; however, it should be stressed that OYANGUREN (1972, 1974) does not mention any occurrences of gas or brine in the Esparza potash deposit.

In conclusion, the excellence of the comprehensive measurement data obtained at the Esparza mine is re-emphasized; some re-interpretations of the measured data are necessary. The fact that the writer did not include Figs. 7-34 through 7-36 in his 1974 publication appears to indicate that he dropped the stress arch hypothesis.

7.5 CONTROLLED SOLUTION MINING

7.5.1 General Remarks

The Solution Mining Research Institute is devoting increasing research to subsidence problems experienced in recent years. Serious difficulties developed at various locations as a result of uncontrolled solution mining; for details, the reader is referred to PIPER (1978). Some case histories of uncontrolled solution mining are dealt with in Chapter 6.

Solution mining in salt deposits became particularly attractive during the past decades as many countries decided to use solution-mined caverns in salt deposits for the storage of hydrocarbons. In some countries, e.g., in France and in West Germany, still increasing numbers of large storage facilities were established by controlled solution mining of salt caverns. Other countries, e.g., the U.S.A., appear to concentrate their immediate efforts on existing salt cavities created for the purpose of salt production by solution mining or conventional mining.

It goes without saying that countries without salt deposits, such as Sweden, are forced to use formations other than salt deposits; apparently, specific problems remain to be resolved as the main advantage of salt deposits, their absolute impermeability under certain depths of burial, is missing.

The term "controlled solution mining" as used in this text refers to the excavation of single individual caverns, or of interconnected caverns lined up in a single row; adequate control of size and shape of the caverns, preferably by sonar logging or comparable techniques, is necessary. Details of such measurements, and some problems encountered in single caverns, are dealt with in I/4.2.4.

In multiple-cavern storage facilities and in brine fields operated for the purpose of salt extraction, the distance between the individual caverns is a crucial design parameter. The salt masses left unextracted between individual caverns are frequently called pillars as in conventional mining operations. Needless to say that such pillars must have sufficient supporting capacity if detrimental effects on overburden formations, and surface subsidences are to be prevented.

In this regard, there is little difference between the various possibilities of salt extraction from buried deposits; it should be borne in mind, however, that wet extraction methods such as solution mining differ from dry conventional mining methods in two important aspects:

1) Solution mining from the surface results in stress differences at the face of excavations which are only approximately one half of the stress differences created in dry mining operations at comparable depths.

2) Solution mining results in wetting of rocks around the excavations, while rocks around dry salt mining operations normally can absorb moisture only from the air ciculating through the openings. Frequently, the rocks around mine openings are dry as implied by the term "dry mining". However, in any case of controlled conventional mining, such effects are restricted to rock near the exposed surface of mine openings due to the absolute impermeability of salt rocks under certain conditions dealt with in I/3.6.

Exact data on surface subsidence caused by controlled solution mining are extremely scarce. Most operators and numerous writers maintain that no subsidence whatsoever is detectable. Considering the dimensions of the individual caverns and of remaining support pillars, one may question such claims in certain cases of controlled solution mining, particularly in cases where the overall extraction ratios appear rather high.

In view of this situation, the following case histories are particularly appreciated, although the term "controlled solution mining" may not be applicable to all phases of salt extraction in various brine fields described by WASSMANN (1978). It is very much appreciated that the writer provided a copy of his report as soon as its presentation at the V Int. Symp. on Salt had been announced. The following discussion is based on said copy. For this reason the wording in quotations is not necessarily identical with the edited version published in the proceedings.

7.5.2 AKZO Zout Chemie, Hengelo, The Netherlands

According to WASSMANN (1978) solution mining started in 1918 near Hengelo, some 10 km from the international border with Germany, see Fig. 7-37.

Until 1952 the first brine field in this area (Boekelo) produced approximately 1.5 million metric tons of salt from 8 single production wells. According to the writer, precise surface levels taken in 1977 confirmed that no subsidence whatsoever had taken place.

Considerable subsidence developed above brine fields in other parts of the lease (called concession in the following figures).

Apparent differences in the reaction of the overburden to salt extraction in this area are attributable to the geology of the lease. A geological section, Fig. 7-38, shows the 50-m salt bed, dipping at approximately 8°, is overlain by 180 m of "red beds" (claystones, dry, tight, impermeable), followed by 0 - 120 m of "Muschelkalk" (marl, dolomitic limestone), and 120 m of unconsolidated near-surface "clay" with some sand.

Above the Boekelo brine field just outside the southern concession border of Fig. 7-39, the total overburden thickness exceeds 500 m and includes 120 m of competent limestone. The northern erosional edge of the limestone is shown as "Border Muschelkalk" at depths around 300 m.

The overlying Tertiary and Quaternary formations "consist of an unconsolidated, very plastic clay with only some sand in the upper thirty metres"; the total thickness of these unconsolidated strata is

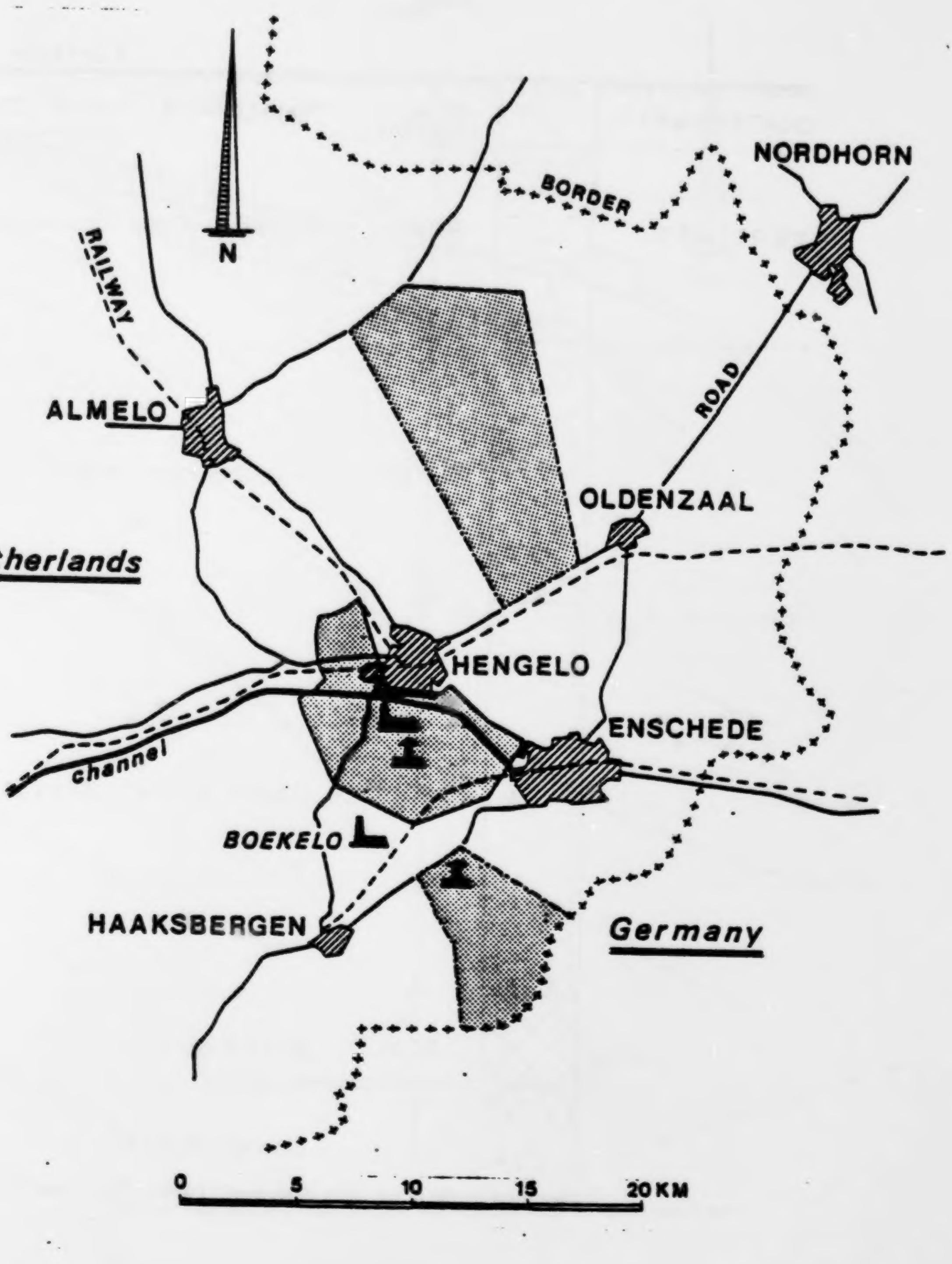
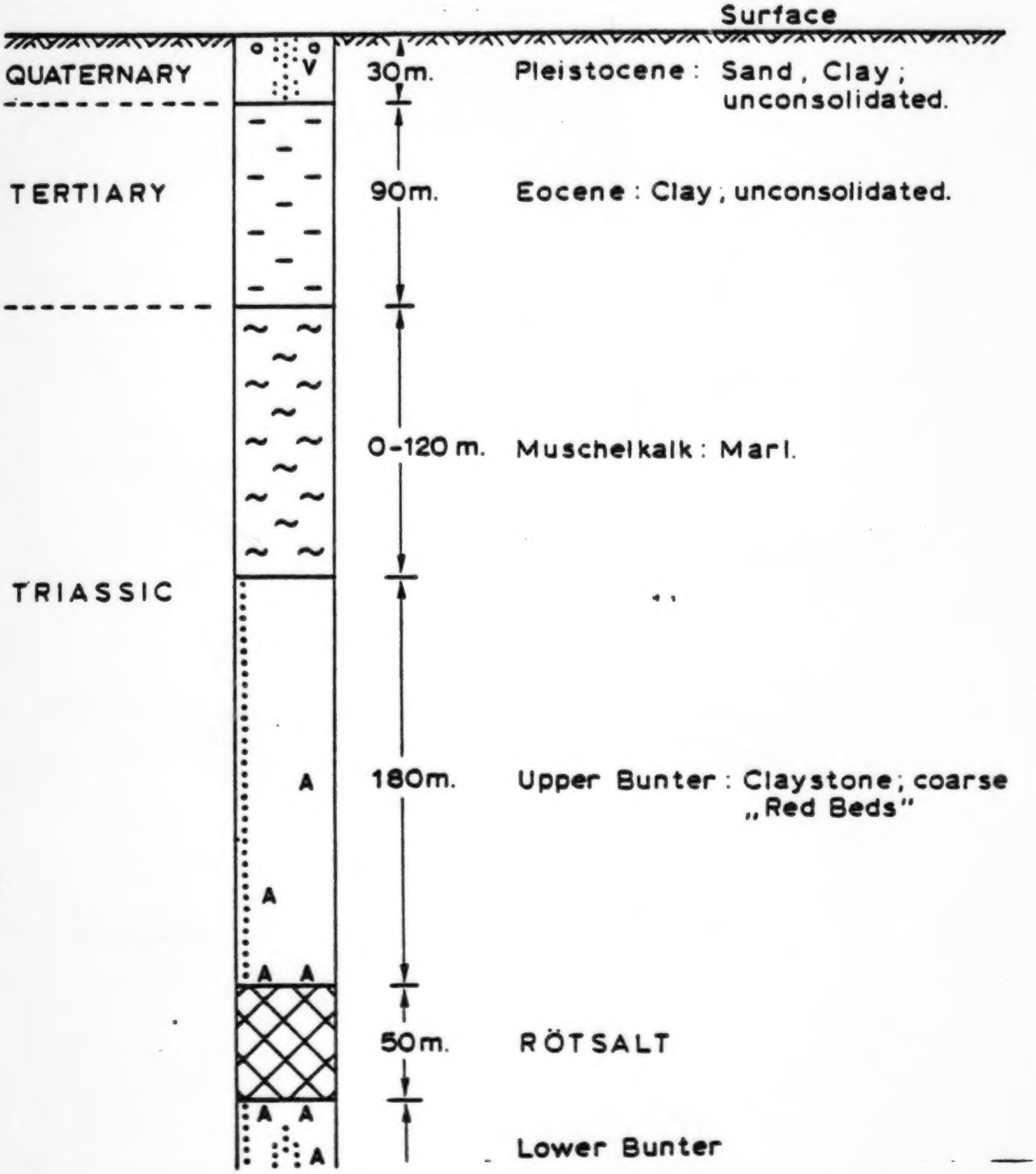
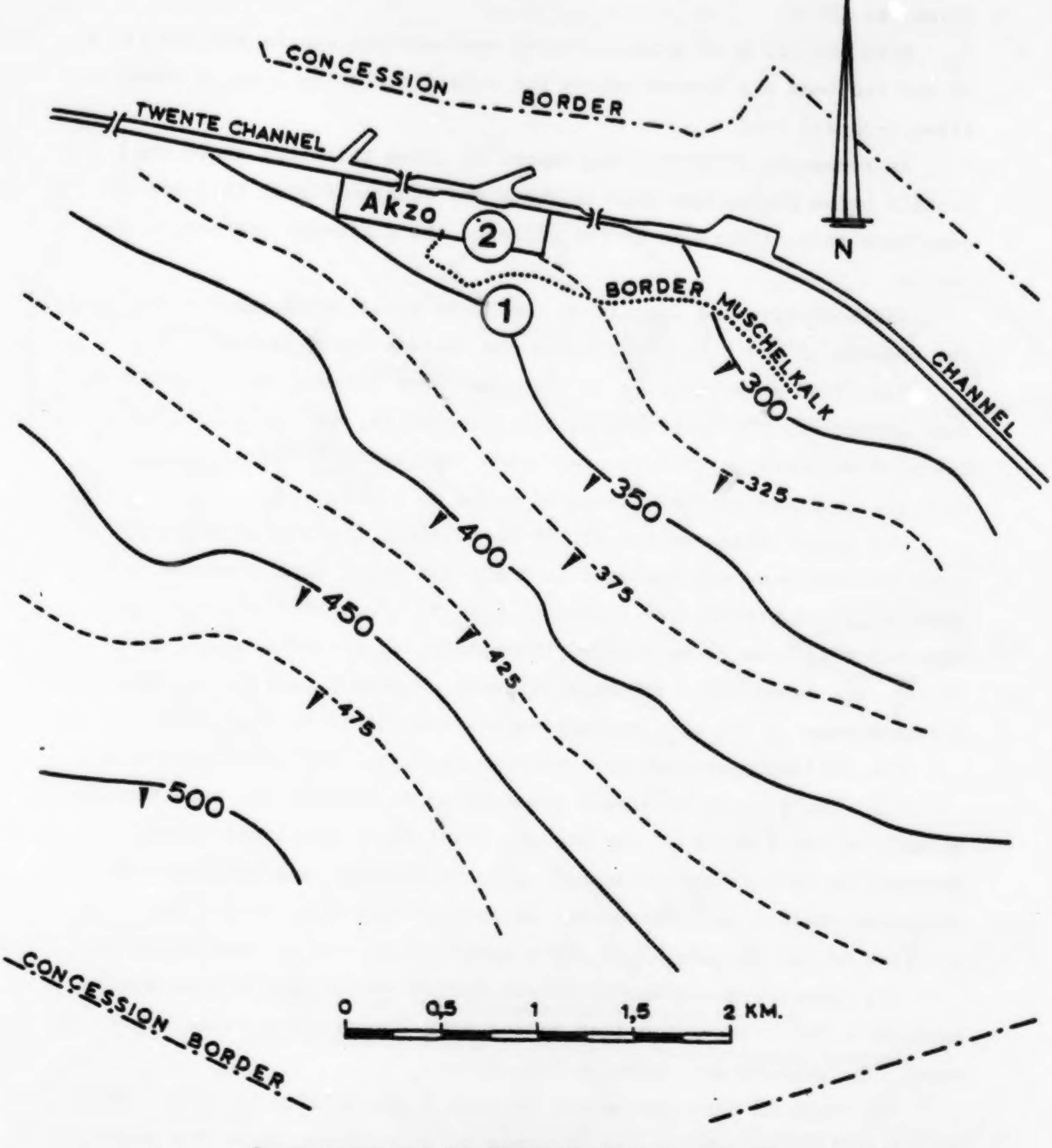


Fig. 7 - 37: AKZO Zout Chemie, Hengelo, The Netherlands (WASSMANN, 1978)


Surface
QUATERNARY
30m.
Pleistocene : Sand , Clay ; unconsolidated.
TERTIARY
90m.
Eocene : Clay , unconsolidated.
0-120 m.
Muschelkalk : Marl.
TRIASSIC
180m.
Upper Bunter : Claystone, coarse „Red Beds"
50m.
RÖTSALT
Lower Bunter

Geological profile of the Akzo concession "Twenthe Rijn", east Netherlands.

Fig. 7 - 38: AKZO, geological section (WASSMANN, 1978)



Structure map on top of the Hengelo salt with the areas of subsidence 1 and 2.

Fig. 7 - 39: Structural geology, AKZO (WASSMANN, 1978)

given as 120 m.

Both the 120 m of unconsolidated near-surface strata and the 180 m of dry red beds are present above the subsidence areas 1 and 2 shown in Figs. 7-38 and 7-40.

As competent limestone is present in 120-m thickness above the Boekelo brine field, but missing above the Hengelo field, this writer considers this difference as the cause of the different overburden behavior.

WASSMANN gives no details on the 120-m limestone formation and on the spacing of the 8 brine wells in the Boekelo brine field.

Fig. 7-40 shows details of the subsidence areas 1 and 2: the surface situation, the locations of the brine wells, and an outline of the cavities as constructed from production figures. The writer assumes that the cavities resemble inverted cones as shown.

The writer stresses the following points: in area 1 the first surface subsidence was measured in 1963; ten years later, another subsidence trough started developing in area 2. From 1963 to 1973, the subsidence in area 1 was studied thoroughly, so it was possible to predict the development of the subsidence of area 2, and to prevent severe damage to the salt production plant outlined on Fig. 7-40.

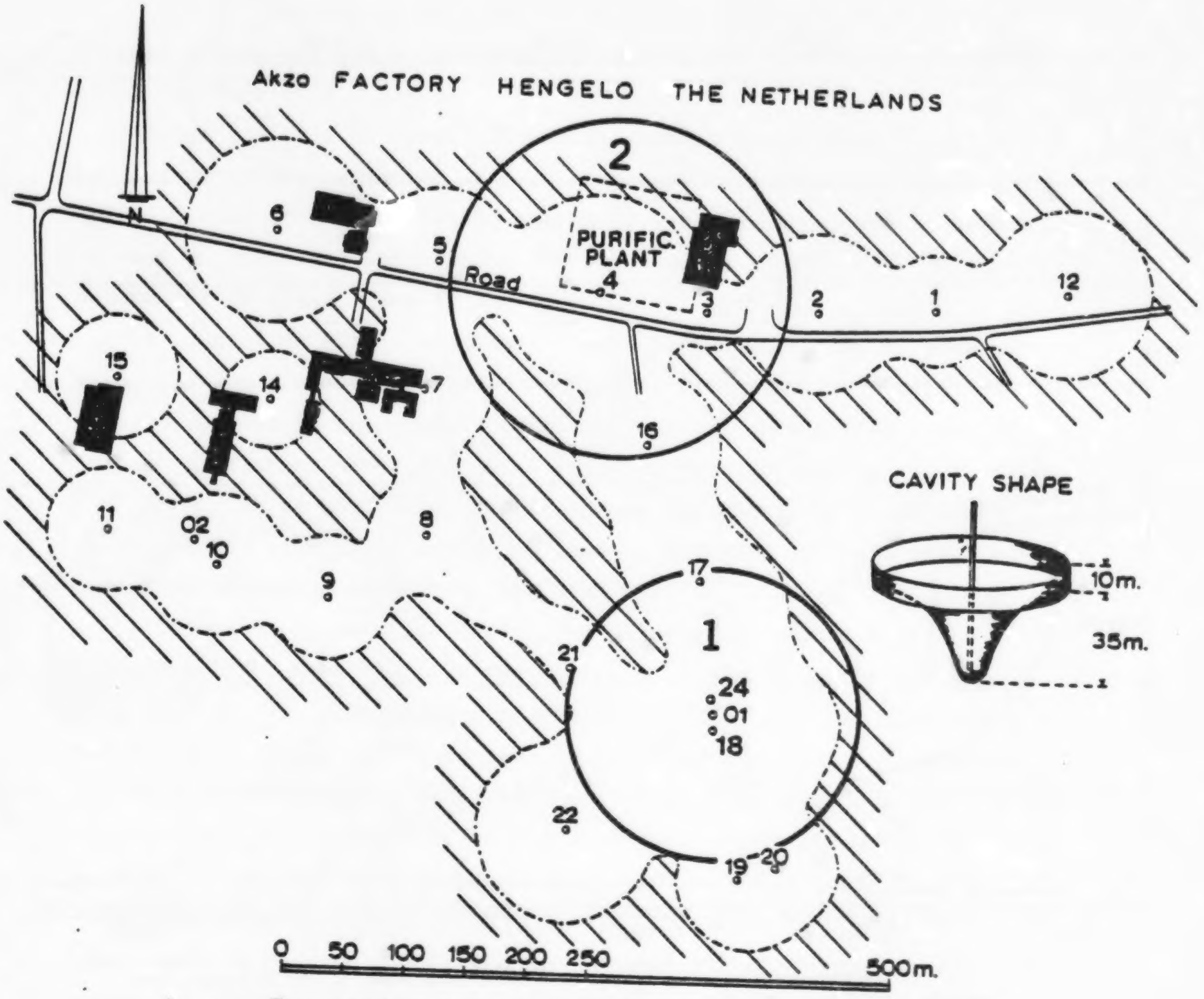
The following details are reported regarding the subsidence area 1:

(1) The 8 wells in area 1 produced approximately the same tonnage of salt as the 8 wells of the Boekelo brine field mentioned above. However, in area 1, the production rate was higher, and the cavities coalesced (became interconnected) as indicated on Fig. 7-40. The cavities in the Boekelo brine field are believed not to have coalesced.

(2) Precise measurements of vertical displacements of the benchmarks of a N-S observation line across area 1 were taken twice every year. The results are shown in Fig. 7-41

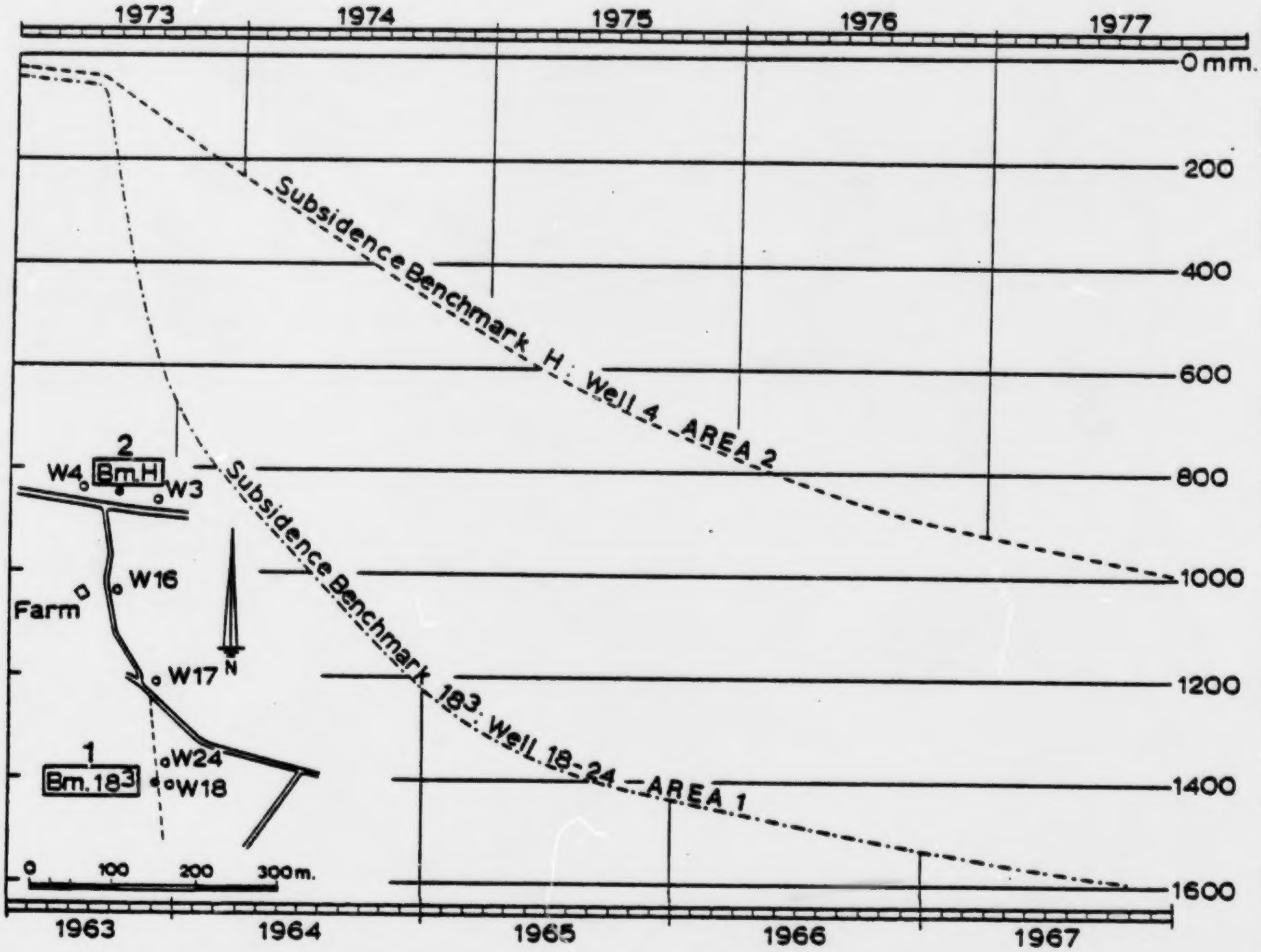
(3) Well 18 near the center of area 1 was drilled in 1949. Well 24 was drilled in 1951 at the distance of only 25 m. These two wells were taken out of production in 1958, five years prior to the first measured indication of surface subsidence of benchmark 18.

(4) The second set of measurements taken in 1963 indicated 30 centimetres of subsidence in the center of a developing subsidence trough. Fig. 7-41 shows nearly 70 cm of maximum subsidence during 1963.



Reconstructed cavities based on salt production figures, Akzo Hengelo, Netherlands.

Fig. 7 - 40: AKZO, subsidence area 1 and 2, assumed cavities (WASSMANN, 1978)



Comparisons of the rate of subsidence of bench marks in the two subsiding areas, Akzo Hengelo, Netherlands.

Fig. 7 - 41: AKZO, cumulative subsidence of two benchmarks (WASSMANN, 1978)

(5) At the end of 1964, 1.2 m of maximum subsidence were measured.

(6) During the two following years, an additional 46 cm of maximum subsidence occurred, averaging 9.3 cm/yr.

(7) At the time of writing (1978), i.e., 15 years after the subsidence trough had begun to develop, the rate of maximum subsidence was still approximately 6 cm/yr.

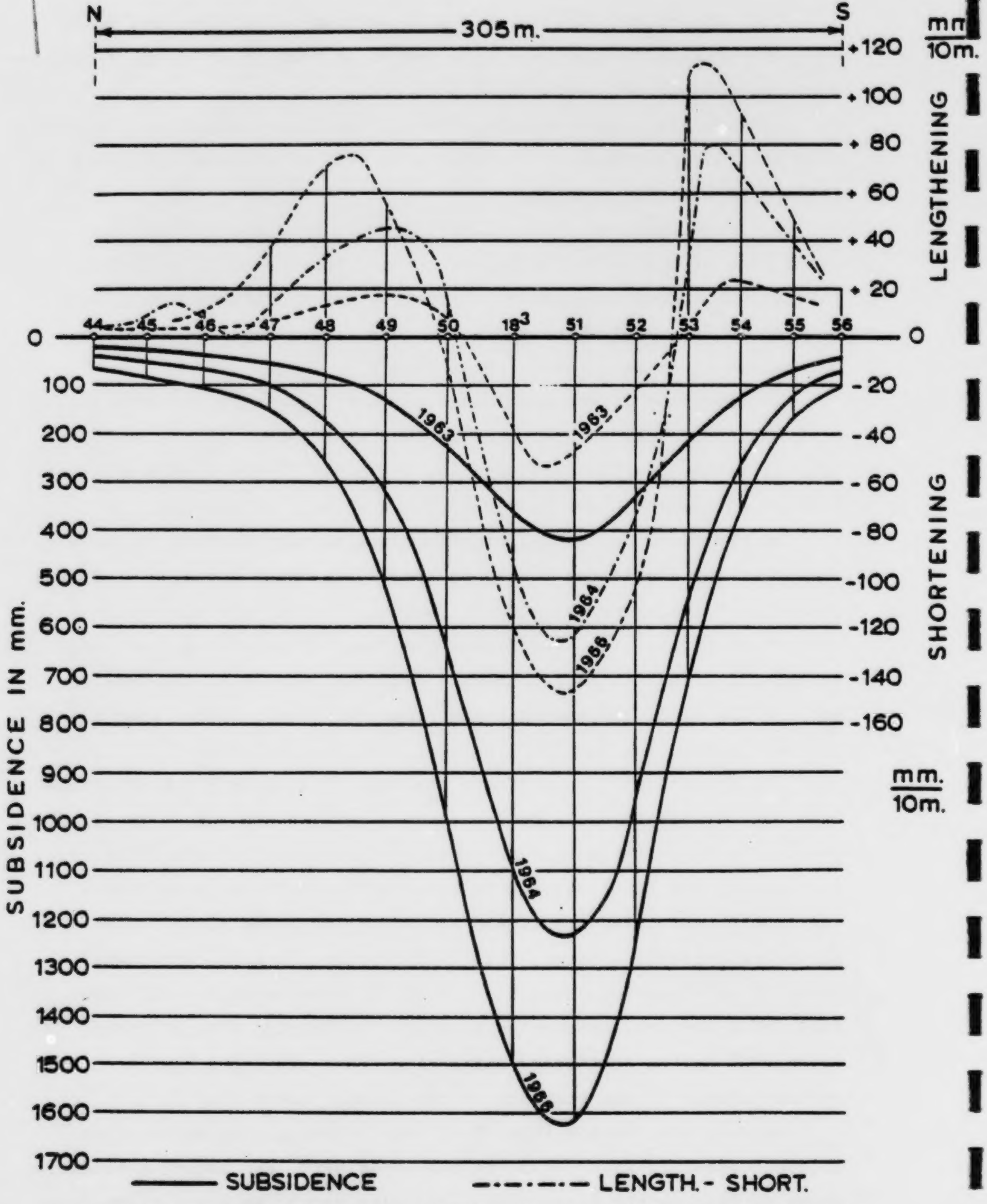
In an analysis of these figures it must be borne in mind that the exact time of the beginning of accelerated subsidence is not known. The initial subsidence rate in 1963 certainly was the highest rate, as can be seen in Fig. 7-41 which shows the cummulative subsidences of two benchmarks in areas 1 and 2, respectively.

A comparison of the subsidence curve of benchmark 18^3 in area 1 with subsidence curves presented in Chapter 2 leaves little doubt of tensile failure in the overburden as the cause of the sudden onset of surface settlement after nearly 15 years of salt extraction.

Referring to horizontal displacements associated with the development of the subsidence trough in area 1, WASSMANN stresses similarities with subsidences measured in Dutch coalfields above stationary extraction fronts, see Fig. 7-32: the point of zero strain in the horizontal direction (lengthening = tensional strain in the tension zone of Fig. 7-1, shortening = compressional strain inside that zone) did not move during the four years of measurements covered in Fig. 7-40.

The writer fails to indicate the significance attributed to this observation; his emphasis on "the stable zero strain point" in Fig. 7-42 appears to reflect theories proposed by GROND (1957). According to ABEL (1970) see Fig. 7-43, GROND shows a "stable break plane" at a stationary extraction front, and an "advancing break plane" at an advancing extraction front; this "limit plane for ground movement" ahead of an advancing extraction front is shown advancing with the face (of a longwall extraction panel). The "mining induced ground movements" at the stationary extraction front are shown completed without any change of the position of the "stable break plane".

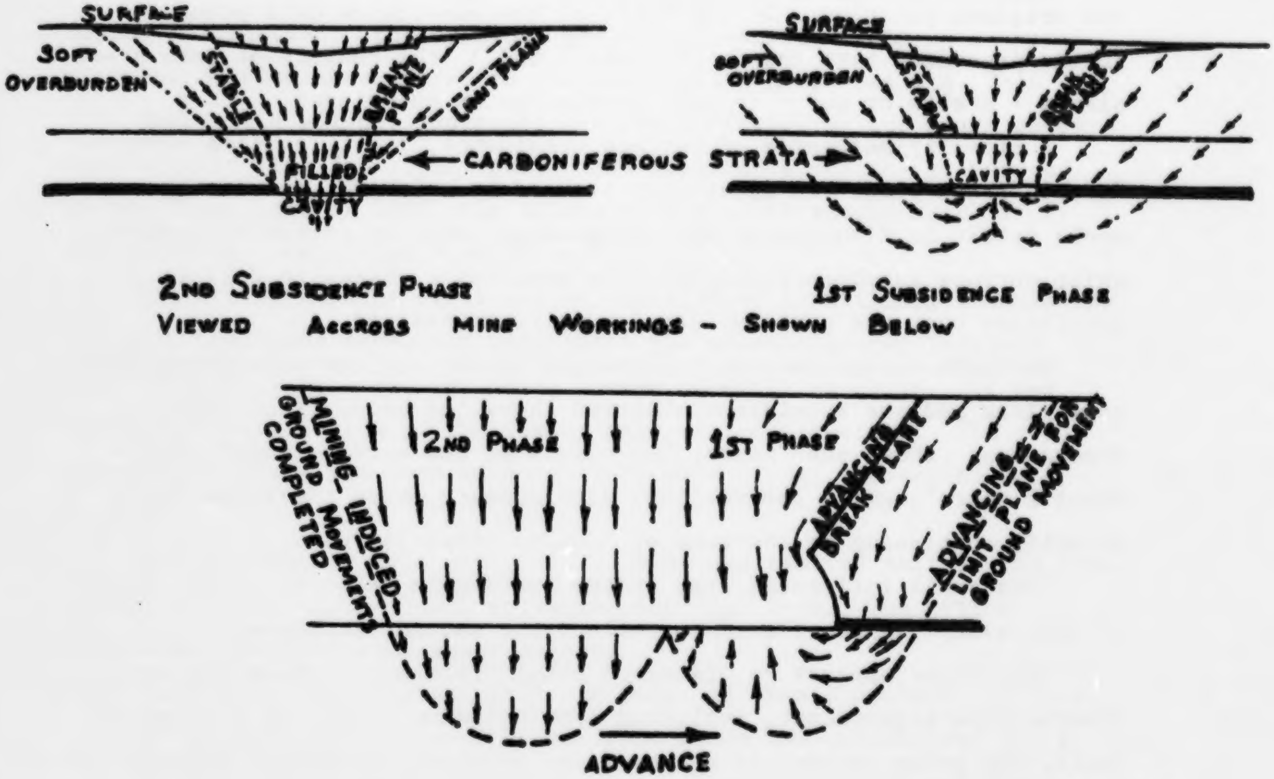
Readers who compare Figs. 7-42 and 7-43 should be aware of an apparent error in Fig. 7-43: in the upper part, the second subsidence phase in fact is the first phase, and vice versa, as the surface intersection of the "limit plane of ground movement" is supposed to move



Results of measurements of the horizontal and vertical displacements of bench marks in area 1 during the period 1963–1966.

Fig. 7 - 42: AKZO, measured displacements 1963-1966, area 1

(WASSMANN, 1978)



Movement trajectories around a longwall face. (Modified from Grond, 1957).

Fig. 7 - 43: Subsidence characteristics, longwall coal mining (ABEL, 1970, modified from GROND, 1957)

out to increasing distances from the "stable break plane" during the second phase of surface subsidence.

In other words: the "limit plane of ground movement", identical with the angle of draw shown in Fig. 7-1, has not a fixed position, while the point of zero strain shown in Fig. 7-42, is postulated to remain at the original position. On the basis of the subsidence data presented in the preceding text and in Chapters 2 and 3, the reality of such break planes - stable or not - in soft overburden is questioned.

A dip-slip mechanism of surface subsidence, i.e., faulting along a "stable break plane" as apparently assumed by WASSMANN, inevitably would result in flooding of any conventional salt or potash mine above which surface subsidence occurs. The remarkable change in related hypotheses over the past two decades is re-emphasized.

WASSMANN emphasizes two differences in the surface subsidence above coal mines and the subsidence observed above the brine field under discussion: above coal mines, "movements at the surface ended after about 2 years", while the vertical displacement above the brine field is still continuing at the rate of 5 cm/yr after 15 years.

"The small influenced area at the surface in relation to the depth of the cavity" is considered to reflect the second difference.

The writer appears to disregard other differences which are considered more significant, including the following fact: in a brine field, the brine present in the cavities provides overburden support which amounts to roughly one half of the deadweight of the overburden; this support exists at all times.

Additional support is supplied by non-dissolved salt between individual cavities. However, it is difficult to assess this additional support in brine fields such as those shown in Fig. 7-40. The reasons are as follows:

Fig. 7-40 is based on assumptions regarding the flow patterns of fresh water towards the production wells. Considerable salt "pillars" may have been left underneath area 1 when wells 18 and 24 were taken out of production in 1958, leaving saturated brine in the cavities.

WASSMANN acknowledges difficulties in determining exactly the salt production from each individual well "because of the numerous existing connections" between cavities of neighboring wells. This gives reason to assume that indeed salt pillars were existing underneath the brine fields and assisted in controlling the overburden subsidence.

WASSMANN refers to an exploration hole drilled in the center of subsidence area 1 for the purpose of obtaining more information on the actual underground situation. As the two neighboring holes 18 and 24 are only 25 m apart, see Fig. 7-40, the exploration hole 01 provided unique information: the original geological section could be compared with the section encountered in the exploration hole, see Fig. 7-44.

There is a slight, insignificant contradiction in the exact dates: according to Fig. 7-41, the accelerated subsidence started at the end of the first half of 1963; the legend to Fig. 7-44 should read "after two years of accelerated subsidence."

The writer reports difficulties experienced in drilling through the Triassic limestone formation underneath the unconsolidated Tertiary near-surface claystones, including losses of drilling fluid. It was decided to core 68.4 m of the deeper part of the limestone. The core recovery of 65.3% was poor in comparison with normal recoveries next to 100%.

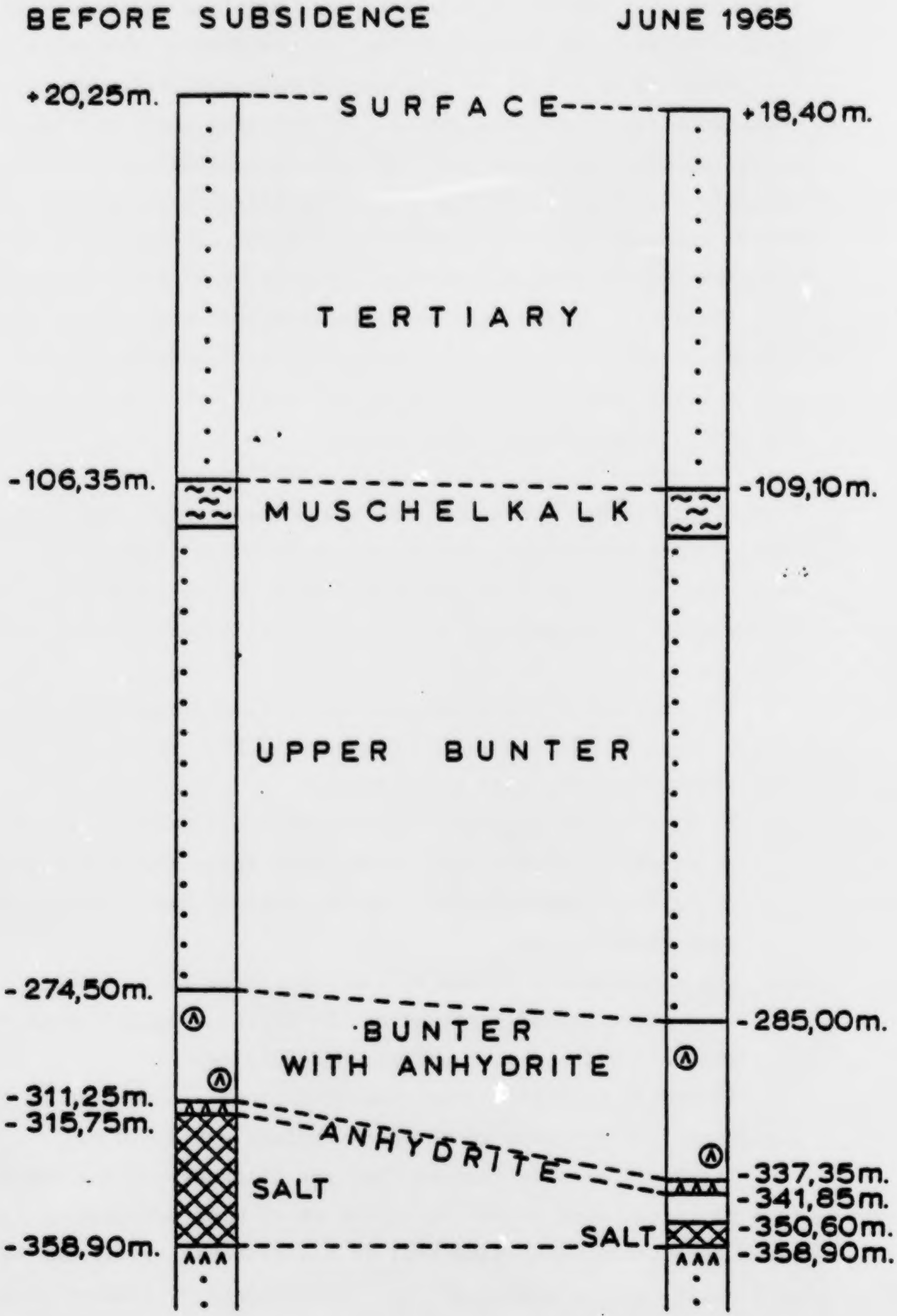
The exploratory hole detected 8.3 m of undissolved salt at the basis of the original 43.15-m salt sequence, see Fig. 7-44. The writer emphasizes the following observations:

(1) 34.65 m of the original salt sequence had been dissolved. 8.75 m of solution residue were accumulated above the undissolved 8.3 m of salt; apparently, the solution residue had already undergone some recompaction.

(2) The 4.5 m anhydrite bed at the top of the salt had been lowered from its original position at the depth of -315.75 m to -341.85 m, indicating 26.10 m of underground subsidence.

It should be noticed that the elevations are related to the normal sea level; the original depth below surface was 336.0 m.

It should also be noticed that the thickness of the anhydrite bed (4.5 m) is the same before and after 26.10 m of subsidence. This indicates a competent anhydrite bed; in all probability, it had been fractured vertically, and consisted of individual blocks of unknown size. Apparently it showed so-called pseudo-plastic behavior and could perform subsidence with little or no delay while salt extraction was in progress.



Geological profile of the Akzo Well 01 after 2½ years of subsidence.

Fig. 7 - 44: AKZO, geological section of exploration hole 01 (WASSMANN, 1978)

(3) In contrast to the unchanged thickness of the 4.5 m anhydrite bed, the thickness of the overlying Bunter claystone with anhydrite increased from 36.75 m to 52.35 m, compensating for 15.6 m of the subsidence of 26.1 m at the level of the anhydrite bed.
As a consequence, the top of the Bunter with anhydrite was lowered by only 10.5 m (from -274.5 m to -285.0 m).

(4) The overlying Upper Bunter (plus limestone remnants) increased in thickness from 168.15 to 175.9 m, compensating for another 7.75 m of the subsidence at the level of the anhydrite bed.
The basis of the unconsolidated Tertiary was lowered by 2.75 m (from -106.35 m to -109.10 m).

(5) In another significant contrast, the near-surface Tertiary increased in thickness from 126.6 m to 127.5 m, i.e., by 0.9 m.

(5) The remaining 1.85 m (2.75 - 0.9 m) of the 26.1 m of subsidence at the level of the anhydrite bed were measured as surface subsidence. According to WASSMANN, the following conclusions were drawn from the data established in the exploratory borehole:

(a) The Quaternary and Tertiary clay formations near the surface possess a degree of plasticity sufficient to prevent rupture or faulting.

This conclusion is supported by the facts under (5) above; the slight increase in thickness (0.9 m) may have been caused by any combination of a number of possible processes, including changes to the water saturation of near-surface sand layers and alterations of clay minerals, and the plastic deformation itself.

(b) The Triassic formations are completely broken; open fractures and small cavities with dimensions of several metres were detected during drilling and logging.

(c) Collapse of roof formations caused the complete closure of the void created by dissolution of 34.65 m of salt, see (1) above.

The writer continues stating that the original cavity with the height of 34.65 m was partly filled with solution residue. The cavity "collapsed several years after the shut-down of the wells" (in 1958); it is postulated that "the structural failure of the roof formations is not only due to the big span of this roof."

To prevent any misunderstanding of these statements and postulates, the following points are emphasized:

(1) The actual spans of the dissolved cavities are not known. Fig. 7-40 shows an assumed outline of cavities. There are reasons to assume that salt pillars remained underneath the subsiding areas and reduced considerably the span of the roof supported by brine.

(2) The immediate roof of the dissolved salt sequence, the 4.5 m anhydrite bed, apparently did not significantly affect the underground subsidences due to its pre-fractured state, as outlined above.

(3) The overlying Bunter red beds with or without anhydrite probably resemble similar red beds encountered above numerous other salt deposits. The structural stability of such red beds has been thoroughly investigated in numerous potash mines, e.g., those extracting the Stassfurt potash bed, those extracting the Upper Rhine potash beds, and those extracting the uppermost potash bed of the Canadian Prairie Evaporites. Such red beds are usually intersected by numerous vertical fractures, have no structural stability to speak of, and their instability is utilized in extraction methods with intentional roof caving, see 7.4.

For these reasons, the assumption of water adsorption to initiate structural failure of the red beds, as theorized by WASSMANN, appears not necessary. Such beds may collapse when the spans of openings have normal entry width of about 5 m, or extraction room widths of 10 - 20 m, or any greater width, depending on the presence of locally unfractured overburden beds, and on other geological conditions which may change from location to location.

As a matter of fact, if indeed water would penetrate due to "capillary forces" upward into the "normally tight and impermeable claystones", the resulting increase in volume of certain clay minerals might result in increased roof stability as the horizontal stresses would increase.

WASSMANN elaborates as follows: "from laboratory experiments on cores a maximum advisable diameter of about 80 m was calculated for the cavities in the Hengelo field. However, in these calculations, changes in the mechanical properties of the roof formations, and especially the red beds, by moistening were not taken into consideration. "Now it is known that water or brine will penetrate" into the roof as quoted above. "But it is considered only to be possible in an upward direction where the internal stresses are more or less released owing to undercutting by the open cavity."

"The walls of the cavity are still under the influence of the overburden pressure and not accessible for penetrating fluids."

"This process will creep slowly but steadily upwards depending on the height of the capillary action, and bank after bank of the roof formations will collapse into the cavity."

Apparently, these opinions are based on the theoretical behavior of an elastic multi-layer plate supported at the walls of an underlying cavity, considerable abutment load concentration near the cavity preventing "capillary action" in horizontal directions.

When such a "clamped plate" of overburden is bending, tensional horizontal stresses develop in its bottom layers, and may result in eventual failure which would proceed upward. However, if "capillary action" penetrates vertically into the roof, causing considerable increases in volume of affected rocks, horizontal compressional stresses would develop as postulated in hypotheses which call for stress arches, stress envelopes or high circumferential stresses all around openings, see 7.2.2. Such hypothetical compressional horizontal stresses are postulated to stabilize the roof of openings rather than to result in roof collapse.

WASSMANN refers to other abandoned wells; it was noticed that the roof of cavities collapsed "in banks of about 10 - 30 metres thickness over the years". Such progressing collapses of multi-layer overburden formations cannot be reconciled with hypotheses of stable stress envelopes referred to above, and of "pressure arches" as postulated by WARDELL (1958 - 1968).

Apparently, the progressing collapses reflect contrasting hypotheses of clamped elastic plates which deflect excessively when their unsupported span exceeds certain threshold values. With reference to Figs. I/5-9, I/5-11, and I/5-13A, and to the subsidence characteristics shown in the preceding text, it is re-emphasized that there are indeed many similarities between observed subsidences above extracted coal seams and extracted salt and/or potash beds.

However, it must be considered that abutment loads decrease when a multi-layer roof formation collapses progressively. The recompaction of fragments of all sizes, from fine-grained solution residue to blocks

10 - 30 m thick, controls the surface subsidence.

The real problem in analysing and interpreting subsidence data such as obtained for area 1 of Fig. 7-39 is re-emphasized: in contrast to conventional mining where the position of extraction fronts at any time is known exactly, the position of the walls of solution-mined cavities in a brine field is not known; it can merely be assumed. There is reason to assume that some large salt pillars were left in area 1, as outlined above; if this was the case, the conclusions drawn by WASSMANN would have to be changed considerably.

The writer summarizes his interpretation as follows: in 1963, the progressive collapse of roof formations in area 1 finally reached the unconsolidated Tertiary clay and from that moment on a pronounced subsidence of the surface was measured. "The compaction of the rubble in the disturbed layers will be responsible for a very slow, decreasing but longlasting subsidence at the surface".

"Yet the small area influenced at the surface with a diameter of only 270 m could not be explained in relation to the depth of the original cavity at 340 m."

The conclusion regarding the effect of compaction of rubble in the cavity is acknowledged; the apparent disregard of other important factors, including the support provided by the brine left in the cavities and the possible support provided by undisolved salt pillars cannot be accepted as it results in misleading oversimplifications.

Fig. 7-42 clearly demonstrates the surface subsidence trough extending fary beyond the quoted diameter of 270 m; the angle of draw cannot be determined exactly because of the unknown extent of the dissolved cavities.

The boundary of the surface subsidence trough is moving to increased distances from the center of the trough, i.e., the angle of draw has not a fixed value; it rather becomes greater in time as the boundary of the subsidence trough moves to greater distances.

In this writer's opinion, the subsidence characteristics of Fig. 7-1 imply that the points of zero horizontal strain, i.e., the boundaries between zones of tension and compression, are moving according to the span of openings. Such shifting may not show in measurements which cover only a few years of a subsidence process that will continue over many decades to come until the limiting value of Fig. 7-1 is finally reached.

These points are stressed particularly in view of WASSMANN's statement that, "after a year of thorough measuring", the situation in subsidence area 2 of Fig. 7-40 could be assessed; "similarities, and also some differences" between the subsidence development in the two areas could be seen.

The writer describes the geological situation and the brine production history of area 2 as follows:

Well 4, located approximately 20 m west of the center of area 2, encountered approximately the same geological sequence as shown in Fig. 7-38 except for the missing 15 m of Muschelkalk (limestone).

In 1959, well 4 was taken out of production; it was connected to several other cavities as shown on Fig. 7-40. Salt production records and the history of repair jobs indicated the cavity shapes. Connections to neighboring cavities were assumed to exist only under the roof of the rocksalt bed, see Fig. 7-45.

Comparing this assumed situation with that assumed for the subsidence area 1, the writer further assumes that there was little space for broken rock material available at well 4.

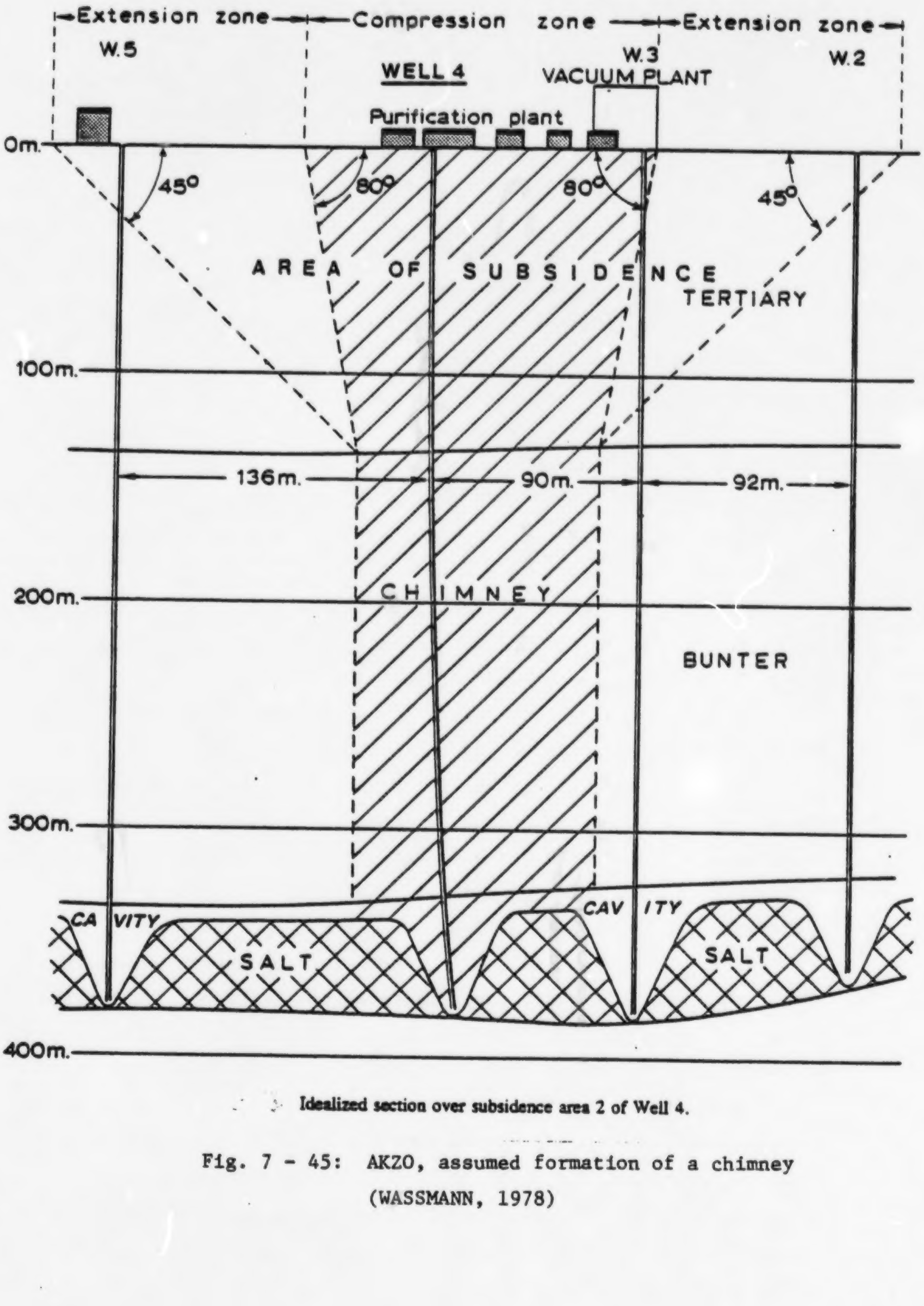
"it was, therefore, no surprise that a much slower rate of subsidence was measured at the surface" in the area of well 4.

This statement is only partly correct as shown in the following discussion. In the first place, it must be stressed that benchmark H is located between wells 3 and 4, see Fig. 7-41. Therefore, it does not indicate the subsidence at well 4 as suggested by the denomination of the respective curve in Fig. 7-41.

Referring to Fig. 7-41, which shows the cumulative subsidences rather than the subsidence rates measured at the respective benchmarks, the writer stresses that "the subsidence rate in area 1 is much higher in comparison to that of area 2 for the first three years".

For the first two years, this statement is not questioned as the two cumulative subsidence curves keep diverging to the maximum vertical distance of nearly 700 mm in 1965 and 1975, respectively.

However, over the following two years, the distance decreased to approximately 600 mm; this means that the subsidence rate of benchmark



Idealized section over subsidence area 2 of Well 4.

Fig. 7 - 45: AKZO, assumed formation of a chimney (WASSMANN, 1978)

H in area 2 exceeded the subsidence rate of benchmark 18^3 in area 1 considerably.

During the last year covered in Fig. 7-41 the subsidence rate of benchmark H continued to exceed that of benchmark 18^3, as indicated by the final slopes of the two curves. These final slopes must be shown as straight lines if indeed constant subsidence rates developed at both locations.

In his text, the writer states the opposite, apparently on the basis of data presented in Table 7-IX which call for final subsidence rates of 80 mm/yr of benchmark 18^3, and 60 mm/yr of benchmark H.

These predictions cannot be reconciled with the correct plot of the cumulative subsidence values of Table 7-IX. The resulting corrected curve of the cumulative subsidence of benchmark H shows much more similarity to the curve of benchmark 18^3. For the following reasons the difference is significant.

The assumptions outlined above led the writer to the rather questionable picture shown as Fig. 7-45:

"The moistening of the roof formation above the existing cavity (of well 4) will create a chimney filled with broken rock material. Depending on the storage capacity of the cavity, this chimney will reach the unconsolidated formations or not. If the unconsolidated clay is reached, a normal subsidence bowl will develop under the angle of draw of 45° for this kind of formation. This explains the relatively small area of influence in relation to the depth of the cavity."

"The plane of break or fracture has been found at a much steeper angle. This plane intersects the surface at a line connecting the points of the largest extensions (of the underground excavation and of the surface subsidence trough). This angle is about 80° in the Hengelo field".

It is re-emphasized that the writer uses definitions which differ from those generally used in the technical literature on subsidence.

Near-surface planes of fracture may develop in certain cases as shown in Chapter 2; the prerequisite, the presence of an elastic roof formation which can bridge certain spans of underground excavations until sudden tensile failure takes place, is definitely not met by claystones and red beds see Fig. 7-42. Such red beds are known for

TABLE 7-IX

Subsidence data, benchmarks 18^3 and H, areas 1 and 2 of Fig. 7-39

NOTE: precise levels were taken twice very year during the months of May and September/October. The listed cumulative subsidences are intrapolated.

	Area 1			Area 2		Prognosis
Year	Cumul. Subs. (mm)	Year's average (mm/yr)	Year	Cumul. Subs. (mm)	Year's average (mm/yr)	(mm/yr)
1962	21	21	1972	21	21	–
1963	675	653	1973	332	311	(311)
1964	1207	533	1974	631	299	300
1965	1414	207	1975	827	196	200
1966	1513	99	1976	940	113	125
1967	1595	82*	1977	n.a.	n.a.	75**
1968	1677	82*	1978	n.a.	n.a.	65**
1969	1758	81*	1979	n.a.	n.a.	60**
1970	1839	81*	1980	n.a.	n.a.	60**
1971	1919	80*	1981	n.a.	n.a.	60**
1972	1999	80*	1982	n.a.	n.a.	60**
1963-1972	1978		1973-1977			1315III

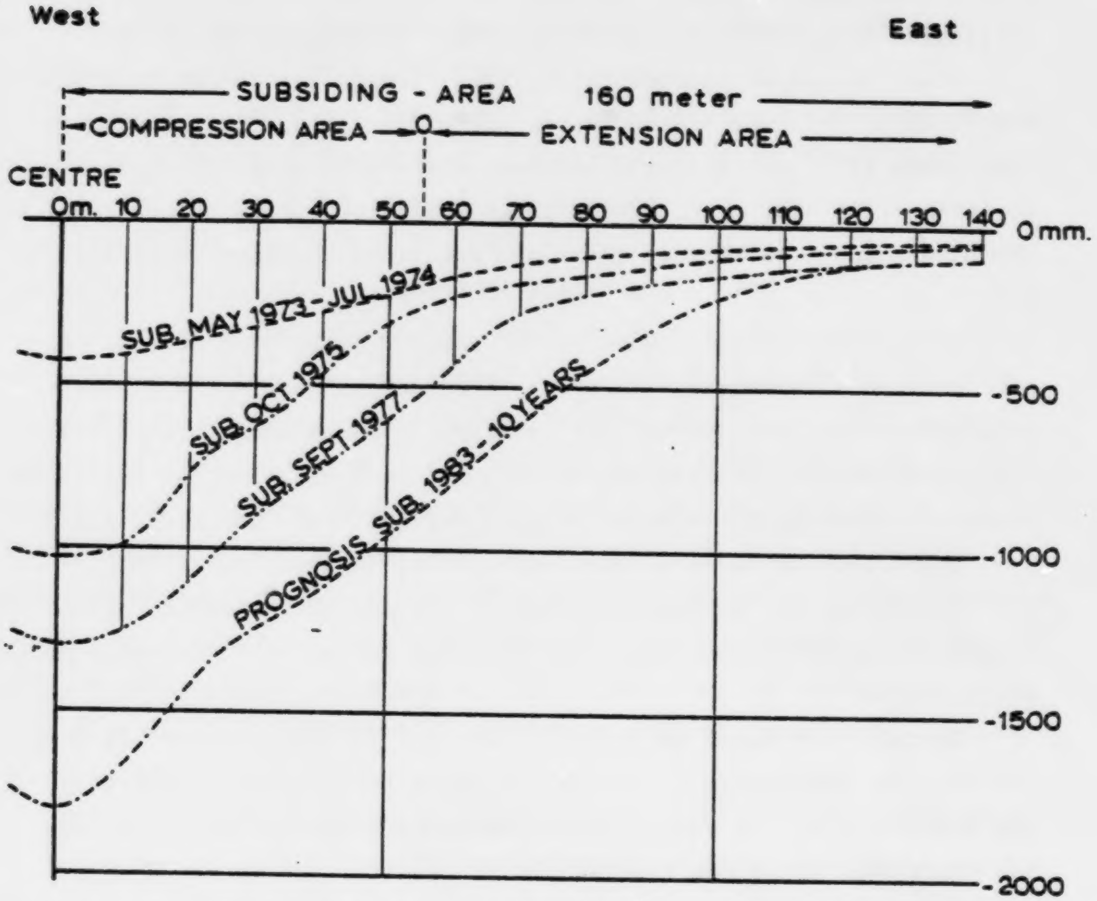
* Too high, see table 7-X

** Too small, see Table 7-X

*** Reached 1977 in center of subs. area, see Fig. 7-46 and Table 7-X.

breaking up easily, and this behavior is utilized in mining methods with intentional roof caving as emphasized earlier.

WASSMANN calculates that "a 15% swelling of the claystone by moistening" is sufficient to fill the cavity at well 4, "and the postulated cylindrical chimney to the basis of the overlying unconsolidated clay at the depth of 135 m, see Fig. 7-45. Using the angle of draw of 45° (more or less the same angle as found in the Dutch coal fields), "the radius for the influenced area can be calculated to be about 135 m. This figure is in extremely good correspondence with the figure actually



Actual measured and predicted subsidence in area 2 during the period 1973–1983.

Fig. 7 - 46: AKZO, Measured and predicted subsidence (WASSMANN, 1978)

actually found in both cases".

At this point, the critical reader may ask the question "why is a chimney postulated near well 4, but not at other wells with similar cavity dimensions, e.g., 6, 12, and particularly 22 shown on Fig. 7-40?"

Regarding the postulated chimney above the cavity near well 4, the writer concludes: "So in this case the slow rate of subsidence is only originated by the compaction of the rubble pile above the cavity".

This conclusion ignores the bulking (loosening) factor of broken roof rock of the type present above the brine field. This factor may come close to 2, particularly in cases where roof strata tend to break up in banks 10 - 30 m thick; the large fragments tumble to the floor of the cavity and come to rest in random positions as shown in detail in 4.3.

As a matter of fact, hundreds of cases of that type of roof failure, with horizontal dimensions exceeding the "maximum advisable diamenter of about 80 m calculated for the cavities in the Hengelo field", have been observed and investigated in German potash mines; these relationships are thoroughly discussed in publications, see Chapters 2 and 3.

There appears to be no need for further explanations.

In view of the unknown location of the actual boundaries of the cavities, the calculated values of proposed angles of draw appear rather questionable.

On the other hand, there is no question as to the mechanism that controls the subsidence above the Hengelo brine field: undoubtedly, the compaction of the rubble which continued accumulating in the cavities for years even after the termination of brining. No matter whether or not the increase in volume due to swelling of clay minerals contributed to the overall volume increase of the rubble, the bulking factor is the decisive parameter - not to mention the possible increase due to conversion of anhydrite into gypsum.

However, with reference to the subsidence characteristics outlined in 7.1, it is re-emphasized that vertical subsidence itself is absolutely harmless to surface structures, even if several metres of surface subsidence occur. General agreement on this point appears to exist in the technical literature. As a matter of fact, it has been shown that even rather sensitive surface structures can be undermined without any harm done to the structures, provided that the dangerous non-vertical components of overburden subsidence are prevented by suitable extraction sequences.

The reader is reminded of PANEK's (1970) quoted statements regarding the effects of horizontal strain, tilt, and curvature: "in order to 'live with' subsidence...one must be able to estimate or predict the numerical values" of all of these parameters.

WASSMANN claims that "this task of utmost importance in keeping the salt factory running" was successfully accomplished: "it was tried to forecast the vertical and horizontal movements at the surface in area 2 for the following ten years". Some of the forecasts made in 1974 are presented in Table 7-IX and shown in Fig. 7-46.

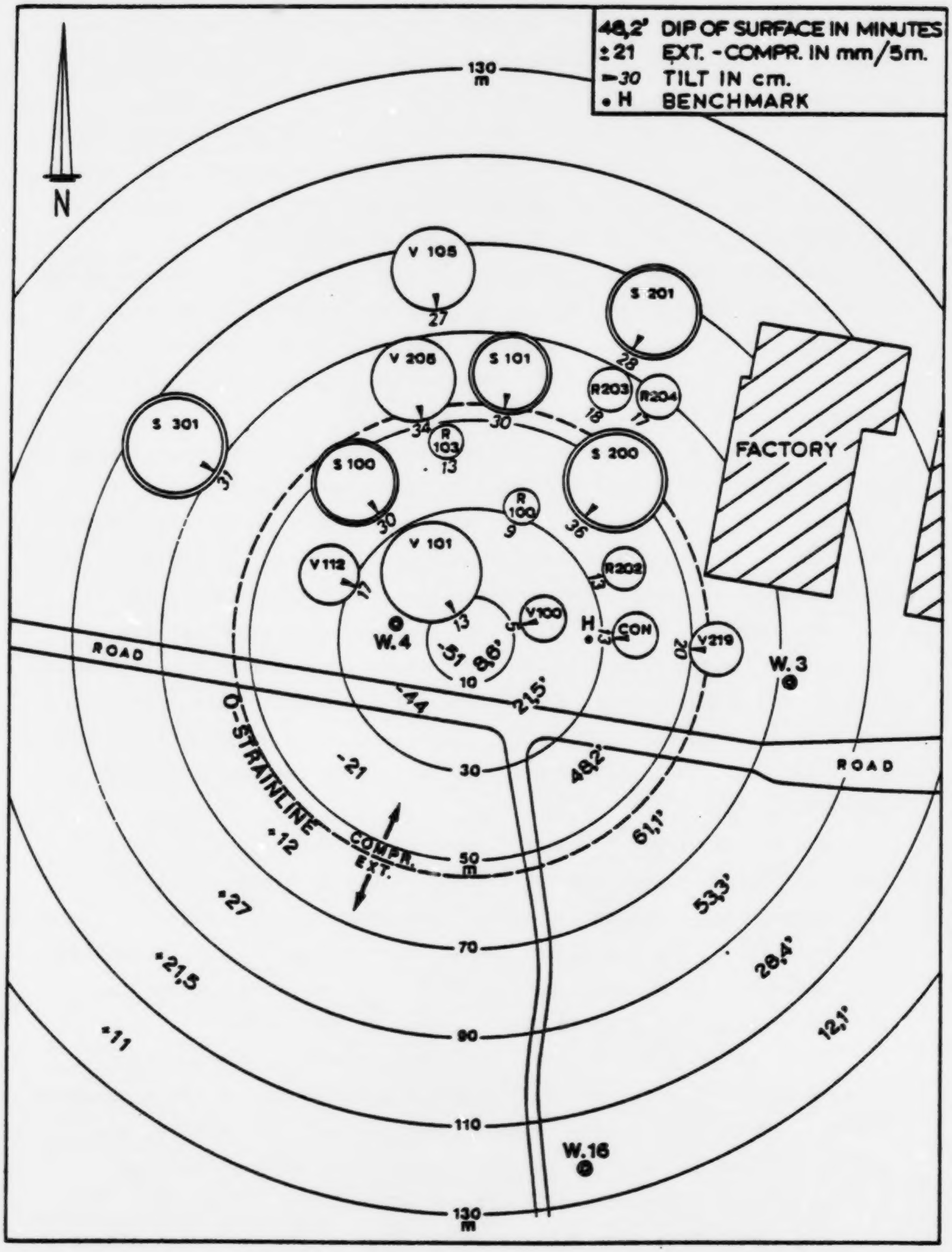
The writer elaborates as follows: the purification plant through which brines are fed into salt factory operates "on an overflow principle, and flow directions could and will be reversed due to differential subsidence. Numerous pipelines would be subjected to horizontal forces and measures had to be taken to avoid rupture of these pipelines".

It appears that the most serious problems were expected from differential subsidence and tilt of numerous purification tanks; needless to say that uniform vertical subsidence of the purification plant would not have affected its performance. The reasons why no attempt was made to achieve such uniform vertical subsidence over the sensitive area are not explained.

The writer gives the exact dimensions of each of the 17 tanks of the purification plant in a table along with the forecasted tilts which are varying with the location in the subsidence trough. Fig. 7-47 shows the locations of the individual tanks, the expected tilt of the surface, and the expected horizontal extensions outside and compressions inside the "zero-strain" circle around the center of subsidence.

These values given in Fig, 7-47 are expected to materialize over a ten-year period after May 1973 when the acceleration of the subsidence started. The writer admits to some idealization: "In reality, the subsidence bowl has more or less the shape of an ellipse with its longest axis in the northeast-southwest direction".

Fig. 7-46 shows some subsidence profiles in the west-east direction, and the profile predicted for 1983.



Predicted figures for tilt and strain at the surface for the 10 year period.

Fig. 7 - 47: AKZO, predicted strain and tilt (WASSMANN, 1978)

The writer's statement that the September 1977 profile "is already nearly halfway the prognosis" appears strange.

For this reason, the vertical subsidence data shown for the center, the 30-m circle (benchmark H), the 50-m circle (approximate zero-strain circle), and the 70-m circle (well 3) were taken from Fig. 7-46 to calculate the data compiled in Table 7-X.

TABLE 7-X

Corrected subsidence data, area 2, Fig. 7-40. Calculated from Fig. 7-46 for points at the indicated distances (0, 30, 50, 70 m), from the center, see Fig. 7-47.

Time period	Data identification	Distance from center of subsiding area (m)			
		0	30	50	70
1 May "73- June /74	Cumul. subs. (mm)	440	315	225	125
	Subs. rate (mm/yr)	377	248	183	107
2 July '74- Sept. '75	Cum. subs. (mm)	1030	625	310	187
	Diff. to 1 (mm)	590	310	85	62
	Rate (mm/yr)	472	248	68	50
3 Oct. '75- Aug. '77	Cum. subs. (mm)	1290	910	620	275
	Diff. to 2 (mm)	260	285	310	88
	Rate (mm/yr)	136	149	162	46
10-year prognos.	Cum. subs. (mm)	1790	1230	940	615
	Diff. to 3 (mm)	500	320	320	340
	Rate (mm/yr)	88	56	56	60
Correct. prognos.	Cum. subs. (mm)		1310		
	Diff. to 3 (mm)		400		
	Rate (mm/yr)		71		

The quoted statement regarding the September 1977 profile refers to the length of the 10-year period beginning in May 1973. At the end of September 1977, little more than 4 out of 10 years had passed; the quoted statement should be read accordingly.

WASSMANN reports as follows on long-term planning of preventive maintenance of the purification plant to offset the expected displacements: "for example, the purification tanks were jacked up and put on a mound of stabilized sand to restore the flow direction between the tanks. The height of these mounds was calculated from the tables (of predicted subsidence and tilt). All tanks were given a tilt in the opposite direction. So it is expected that the tanks will move downward again and tilt back to horizontal position or even more without maintenance jobs to be done within the next five years. The same has been done with a small building with a stiff reinforced concrete foundation and brick walls."

It remains to be seen if the expected effects of what is called long-term preventive maintenance materialize. There is no need for further emphasis on the difficulties involved, particularly in view of the writer's statement that, at the time of writing, 'Only 17% of the volume of the original cavity" are represented in the measured volume of the surface subsidence trough.

Much more surface subsidence is inevitable, according to the subsidence characteristics shown in Fig. 7-1. When the limiting value is eventually reached, the volume of the surface subsidence trough will be 70% of the volume of the original cavities, possibly more, if indeed the deterioration of the overburden due to water adsorption has the effects postulated by the writer.

The crucial question is whether or not the assumptions, on which the predictions are based, are realistic. These assumptions include the formation of a vertical chimney as shown in Fig. 7-45. If such a chimney existed at the onset of the surface subsidence, or continues to exist over the entire 10 year period of measured and predicted subsidences, respectively, much of the non-vertical displacements at the surface which jeoparidzed the operation of the purification plant certainly could not have taken place.

However, the vacuum plant indicated on Fig. 7-45, see Fig. 7-40 for exact location, is bound to suffer serious effects of non-vertical deformations unless the assumptions a) of a permanent chimney, and b) of a "stable" plane of break or fracture, are correct.

Fig. 7-45 illustrates the assumption of a "stable plane of fracture at an angle of 80° with the surface. The measured subsidence profiles of Fig. 7-46 show this assumption incorrect: the October 1975 profile exhibits the maximum curvature, at the distance of 55 m from the center of the subsiding area. Two years later, the maximum curvature can be seen at the distance of approximately 70 m. Fig. 7-46 shows clearly that, during these two years, the maximum increase in tilt took place at the location of the vacuum plant.

The same Fig. 7-46 shows the maximum curvature after 10 years at a distance of about 100 m from the center of the subsiding area. The edge of the predicted subsidence trough is shown stabilized at 120 m since September 1977, limiting the diameter of the subsiding area to 240 m.

Fig. 7-47 shows quite contrasting dimensions: the subsiding area is shown extending well beyond the distance of 130 m, i.e., to a diameter of approximately 370 m.

The latter diameter of 370 m, and the postulated angle of draw of 45° apparently were used to arrive at the diameter of approximately 100 m of the postulated cylindrical vertical chimney through the Bunter claystone down to the salt extraction level.

Apparently, the zero-strain point shown on Fig. 7-46 then was connected to the top of the postulated vertical chimney, giving the angle of 80° between the horizontal surface and the postulated "stable" fracture plane.

Due to the apparent construction of the location of the postulated chimney as outlined above, the eastern edge of the bottom of the chimney is shown at a rather strange location, namely above the cavity of well 3. According to Fig. 7-40, this cavity is connected to that of well 4, which gives the two cavities by far the largest diameter in area 2.

Considering the various contradictions and unqualified assumptions made in the interpretation of the subsidence mechanism, this writer attempted to arrive at more realistic interpretations on the basis of the data presented in Fig. 7-46, and summarized in Table 7-X:

(1) The center of subsidence exhibits a distinct acceleration of the vertical subsidence between July 1974 and Sept. 1975. However, the subsidence rate decreased to 136 mm/year for the following two years; this rate is smaller than that of the 30-m and the 50-m points.

There is no reason for the assumption of 88 mm/yr as the subsidence rate for the remaining years of the 10-year period; compared with 55-60 mm/yr average subsidence assumed for all other points, the rate assumed for the center is far too high.

With reference to Fig. 7-47, it is emphasized that well 4 is located 20 m west of the center of subsidence, while the 30-m point (benchmark H) is located east of the center at approximately equal distances from well 4 and 3. For this reason, the temporary acceleration of subsidence of the center may be attributable to the behavior of the roof of cavity 4 and its extension towards well 5; it is stressed that benchmark H does not show a temporary acceleration.

(2) The curve for the 30-m point, Fig. 7-46, exhibits a course which resembles that of benchmark H.

(3) The curve for the 50-m point shows an acceleration in the average subsidence rate of 162 mm/yr, if real, it would be the highest rate for this period of time.

It is emphasized that the reference point is located above the cavity around well 3, see Fig. 7-47. Whatever may be the cause of the acceleration, it occurred more than one year after the acceleration indicated by the center point. However, it is missing at benchmark H, and at the 30-m point.

For this reason, the acceleration at the 50-m point cannot be attributed to the postulated formation of a chimney as shown on Fig. 7-47. Such a chimney undoubtedly would have included the roof of the cavity at well 3.

(4) The subsidence curve for the 70-m point, located at the distance of less than 10 m from well 3, indicates a virtually constant subsidence rate over the years 1975 - 1977. The assumed increase to 60 mm/yr at the 70-m point over the following 5 years contrasts to assumed decreases at all other points and appears particularly questionable.

Considering the possibility that the temporary increases in subsidence rates shown in Fig. 7-46 may not be real, but reflect slight inaccuracies in measurements or drafting, one can hardly escape the conclusion that the surface subsidence trough developed in a rather normal manner, such as would be expected from the subsidence characteristics shown in Figs. 7-1. As PANEK (1970) suggests, one can live with subsidence and unfavorable characteristics.

However, once virtually constant subsidence rates have developed, the possibilities of arresting the subsidence process appear rather remote: the extracted solids would have to be replaced by solids, unless the fluids occupying the cavities can be confined. This appears difficult, probably impossible, under the given conditions in area 2. The only choice would be to envisage the other possibility of reducing the limiting subsidence by backfilling the cavities with solid material such as sand.

There is no point in creating belief in questionable hypotheses, such as the postulated formation of a stable chimney as shown in Fig. 7-45, when the actual measurements shown in Fig. 7-46 demonstrate the rather normal development of subsidences effectively controlled by adequate pillars in conventional mines.

The reason why the chimney-hypotheses is considered by WASSMANN is apparent from his repeated reference to relatively small areas of surface subsidence, called sinkholes by some writers, see 4.3 and Chapter 6 for detailed discussion of chimney hypotheses.

The following point is particularly stressed: the thickness of unconsolidated overburden must not be taken into consideration in assessing the behavior of underlying overburden strata which are able to bridge certain spans of excavations without causing surface subsidence detectable in short-term measurements.

In the case under discussion, the average thickness of the unconsolidated overburden is 120 m; only the remaining depth to the roof of underlying isolated cavities must be considered when the depth of extraction is compared with the span of extracted areas. In this case, the span was much greater than 180 m, so subsidence had to be expected.

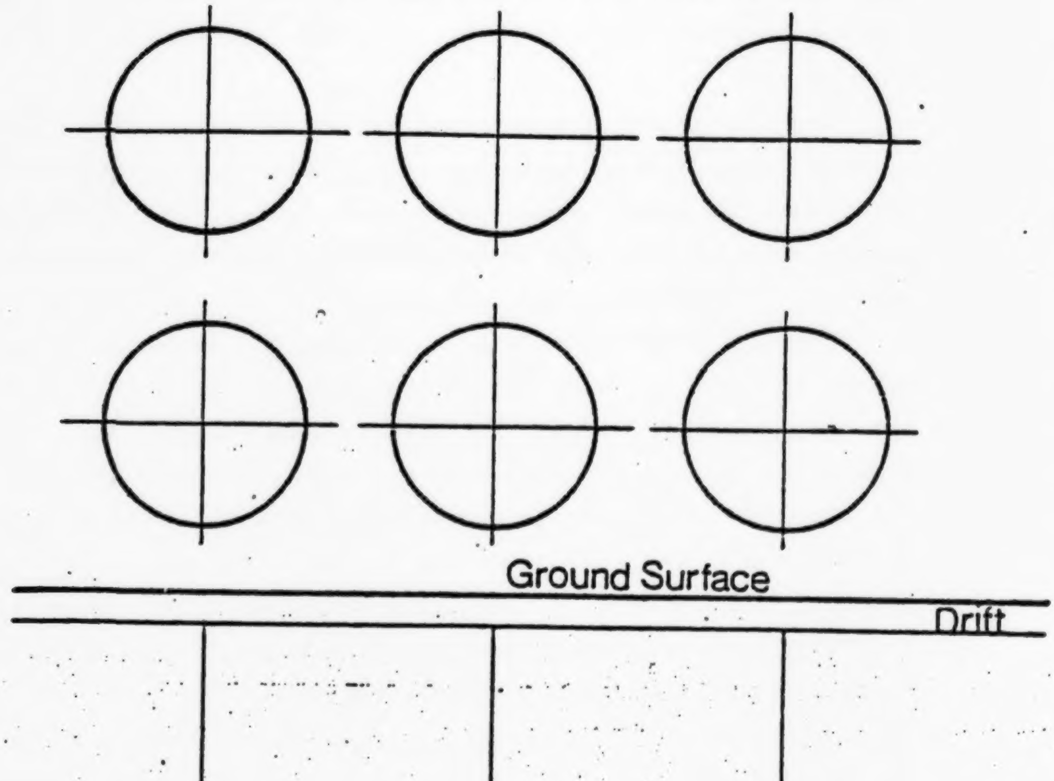
Needless to say that the deadweight of the unconsolidated overburden must be accounted for in theoretical calculations of the span that can be reached without causing measurable surface subsidence.

7.5.3 Cheshire basin, England, U.K.

The geology of the Cheshire basin, surface collapses caused by wild brining, and collapses of conventional salt mines are described in some detail in 4.4.3 on the basis of publications by WALLWORK (1974), and by HOWELL and JENKINS (1977). These writers also report on the successful introduction of the ICI (Imperial Chemical Industries) method of controlled solution mining under the 'dry rockhead', see Fig. 7-48.

SALT: The ICI Controlled System

Plan showing maximum diameters



Section through the Field

Fig. 7 - 48
(COLLINS, 1971)

According to the latter writers, surface subsidence control is achieved "by the orderly solution of large, regularly spaced cavities some 300 feet (90 m) in diameter from boreholes sunk in uncorroded salt beds. These cavities are finally preserved by flooding with saturated brine and no subsidence has been attributed to this technique".

WALLWORK (1974, p. 437) reports: "Subsidence continues to be a major planning problem, although the progressive adoption of the ICI controlled method of abstraction since the 1920's has diminished its impact, particularly in the Northwich area. In 1969, 89% of the brine extracted in Cheshire was obtained by the ICI controlled method. The remaining 11% came from natural brine runs, mainly in the Middlewich-Sandbach area. No brine at all is pumped at Winsford, as production ceased in 1962, being replaced by brine sent by pipeline from the controlled field outside Northwich". It may be mentioned here that the Meadowbank mine dealt with in I/5.2.6, is located just north of Winsford.

"Controlled pumping is assumed not to cause subsidence because the solution chambers are below the wet rock head. Consequently the major problem area is now in the southeastern part of the saltfield between Middlewich and Sandbach. Here output of natural brine has steadily increased since the 1950's, and with it the extent of permanetly flooded land and other forms of subsidence damage".

The ICI method of controlled solution mining offers another significant advantage reported as follows by WALLWORK (1974, p. 438): "In many respects the problem of subsidence was overshadowed in the 1940's by that of chemical waste disposal. The poast-war expansion of the ammonia-soda industry brought with it an inevitable increase in solid wastes...By 1957 about 250 hectares of land in the Northwich area were covered by chemical waste, and only half of this land had been damaged by subsidence...An alternative mode of waste disposal was developed, whereby the slurry could be pumped into the abandoned cavities of the controlled brine wells, without contaminating the rocksalt which was introduced in about 1954, and surface waste disposal became less common...Thus since the mid 1950's one of the major environmental problems has been solved in a singularly effective way".

The writer considers the ICI method of controlled solution mining as best suited to the region on the basis of 45 years empirical evidence. "ICI is the obvious leader, but British Petroleum, and the recently formed British Salt group are equally well supported enterprises whose expansion plans would be best served by controlled pumping" (l.c., p. 439).

WALLWORK (1974, p. 440) concludes that the Cheshire salt-field "clearly shows the benefits which can accrue from the adoption of advanced techniques of solution mining, not only as a means of securing a steady supply of good quality brine, but also as a method of reducing the risk of subsidence to the minimum and of providing receptacles for chemical waste".

The writers referred to fail to provide exact data on the depths below surface of all of the single cavities in the controlled field outside Northwich. Fig. 7-48 shows a plan of the ICI controlled system, and a section through the field (COLLINS, 1971, Fig. 5). As can be seen on the plan, the minimum diameter of the pillar between each set of 4 cavities equals the maximum diameter of 300 feet (90 m) of the cavities. However, the distance between cavities in a row is only little better than 100 feet (30 m), provided the cavities do not exceed the maximum design diameter.

If the section of Fig. 7-48 is drawn to scale regarding the depth below surface of the rockhead, i.e., the top of the salt, the depths exceed 600 feet (180 m); assuming an average increase of 1 psi/foot in vertical stresses, the original vertical stress at the top of the cavities calculates as in excess of 600 psi (x 0.07 = 42 kp/cm^2).

Accounting for the hydraulic support provided by saturated brine, the effective stress difference at the walls of cavities exceeds 300 psi (21 kp/cm^2), thus exceeding the creep limit of salt rocks.

Therefore, it is assumed that the pillars between the cavities are affected by stress relief creep. The small pillars in a row of cavities, see the section, Fig. 7-48, cannot provide full overburden support according to depth and extraction ratio. The much larger pillars in between a set of 4 cavities may have a core which is not affected by creep and provides full support of the overburden, preventing measurable surface subsidences as stated in the reference publications.

It appears essential to secure the impermeability of the roof rocksalt left above each cavity in order to prevent the effects of brines penetration into the roof as reported by WASSMANN (1978), see the preceding discussion. The shape of the upper section of the cavities according to Fig. 7-48 appears well-suited for this particular purpose. Note the contrast between the cavity shapes in this figure and in Fig. 7-40 (inverted cone).

The principles applied in the ICI controlled solution mining method are quoted as follows (COLLINS, 1971, pp. 7/8; historical data shortened as indicated).

"The basis of controlled pumping is the application of the principles of support in dry mining to what is sometimes termed solution mining. When the salt is mined, pillars and a roof rocksalt are left, adequate for the support of the overburden. Thus the salt is removed by solution from the cavities which are carefully located in the saliferous beds well below the level at which any natural brine would be found, thus preventing the possibility of any interconnection. The cavities are developed to a predetermined size and shape", see Fig. 7-48.

"In the 1890's, the United Alkali Company...found it necessary to introduce water to create the brine for pumping...No Doubt aware of the risk that any cavity created haphazardly would rapidly collapse, the company began, before the end of the century, to develop techniques for the production of stable solution chambers. With the formation of ICI the 'knowhow'...became available for the development of a controlled field at Holford near Northwich in the 1930's".

"Over the last seventy years the techniques have been evolved and improved for the controlled creation of a solution-mined chamber. Cavities are developed within the rocksalt, their shape being controlled by continual measurement using sonar equipment, so as to preserve the stability of the ground above. Water, introduced under a pressure sufficient to raise the brine to the surface, dissolves salt from the cavity walls until the required maximum size and shape are attained, when no more solution is allowed".

"To control the amount and direction of solution a system of water inlet and brine outlet tubes are used in the borehole. In addition the roof of the cavity is protected from solution by a cushion of air or oil. The borehole is sealed with steel tubing cemented into the rocksalt, thus preventing any possibility of leakage. An imbalance in the amount of water put in under pressure and the quantity of brine thus raised to the surface would soon reveal the presence of any leakage, as would a loss of the oil or air cushion used for protecting the roof of the cavity".

"Each cavity is developed over several years until it reaches its maximum size and predetermined form, when it is normally left standing full of saturated brine. The size and spacing of the chambers is related to the thickness of the salt beds being worked, and are such, it is claimed, that the cavities are permanently stable. At Holford where the Lower Keuper Saliferous Beds are approximately 800 feet thick, and at the shallowest point some 400 feet below the surface, the chambers attain a height and diameter of several hundred feet".

"The brinefield now extends over several hundred acres, with boreholes placed on a regular grid pattern (see Fig. 7-48). By this system ICI estimate an extraction rate of 20% is possible".

This writer has nothing to add to these quotations, but wishes to extend thanks to Messrs. HOWELL and JENKINS who provided a copy of the COLLINS - report.

CHAPTER 8

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CHAPTER 8

CONTROL OF FLOOR DEFORMATIONS

8.1 OUTLINE OF PROBLEMS

The geological situation at any individual salt or potash mining operation must be known as exactly as possible when a decision is to be made whether excessive floor deformations must be prevented because of their potential danger.

In conventional salt and potash mining it appears practical to distinguish between openings for long-term service, such as entry systems and workshops, and excavations made for the sole purpose of mineral extraction.

In entry systems, vertical convergence due to continuing creep deformation poses the principal problem in deep mines. In homogeneous salt deposits, roof and floor deformations may contribute equally to undesired closure. In flat-lying, stratified deposits, floor deformations frequently cause most, if not all of the closure problems. Excessive floor heave must be prevented because certain minimum heights of roadways must be maintained for sufficient clearance when the huge machinery is to be relocated.

Economic considerations provide another reason why floor deformation should be prevented: roadways and workshops are paved, and repair costs may become excessive if floor uplift is not prevented.

Stress relief methods to prevent excessive floor deformations in mine openings for long-term service are dealt with in Chapter 1.

The objective of the following text is to show why and when excessive floor deformation must be prevented and how this can be achieved.

Under certain geological conditions, the lateral creep out of the abutment zones of excavations with great spans causes large-scale floor deformations which can be extremely dangerous.

With reference to Chapter 2, disastrous consequences of large-scale floor deformations in German potash mines are re-emphasized as they involved "the loss of many lives and mines".

One important prerequisite for adequate control of large-scale floor deformations is the initiation of overburden subsidence, see Chapter 7.

It should be shown by surface subsidence measurements that there is no delay in overburden subsidence when extraction methods known for causing excessive floor deformations are used.

In room-and-pillar mining, adequate pillar design takes care of potential problems due to floor deformations. However, the required minimum width-to-height ratio may result in prohibitive extraction losses in thick potash beds. Extraction methods such as described in Chapter 7 can be used, provided that overburden subsidence is in progress.

The particular potential danger due to large-scale floor deformations is caused by gases and brines which may be present underneath salt and potash beds or migrate into stress-relieved zones underneath developing extraction panels.

The discharge of fluids from isolated reservoirs underneath salt and potash mines is dealt with in 3.5.

It is re-emphasized that the release of gases is particularly dangerous as the gases expand when entering mine workings.

Brine outflow from isolated reservoirs in which the gas pressure is the driving force can also be controlled by reducing the gas pressure. In some cases, the reduction of gas pressures through boreholes resulted in rapidly decreasing brine outflow rates, see I/4.6.

Another serious problem in controlling floor deformations may arise from solutioning processes in conventional room-and-pillar mines, the pillars being weakened by fresh water or by brines which are not saturated with respect to highly soluble salt minerals. The temperature increase due to backfilling with hot refinery waste has similar effects, as emphasized in I/3.7.1.

One common aspect of such dangerous floor deformations is their principal cause: insufficient restraint against large-scale creep of salt rocks into mined-out panels.

The migration of highly pressurized fluids out of abutment zones into separating roof and/or floor strata is enhancing the effects of other causes of excessive roof and floor deformation. However, it has been known for decades that negative effects of fluid pressure can be controlled safely by drilling holes into developing bed separation voids.

Such solutions to difficulties arising from migrating fluids must not be attempted in cases where brine reservoirs are hydraulically connected to groundwater aquifers, fresh water or non-saturated brines replacing the brines which are released into the mine. These relationships and the danger involved in applying too much pressure in grouting operations near mine openings are dealt with in detail in Chapter 3.

The migration of highly pressurized fluids must be considered as an important factor in many cases of excessive floor deformations.

8.2 INTENTIONAL ROOF CAVING FOR EFFECTIVE FLOOR CONTROL

8.2.1 South Harz district, Germany

8.2.1.1 Geological and historical background

Typical geological profiles of the strata underneath and above potash mines in the South Harz district of Germany are shown as Figs. I/2-16, I/2-19, and I/5-13A. The latter figure also shows schematically the creep deformations which are initiated in developing room-and-pillar extraction panels.

The development of bed separation voids underneath mined-out areas is documented by WILKENING (1958). Fig. I/5-13A shows a schematic section through a mined-out potash extraction panel in the Stassfurt potash bed; it is based on observations in and around mined-out areas in which oil, gases, and/or brines were forced out of a cavernous dolomite formation underneath a potash mine.

It is apparent from the reference figure that the thickness of the rock salt sequence between underlying formations and mine-workings represents the most important factor in designing extraction methods in this mining district: the rock salt sequence, providing an impermeable seal against the gas and/or brine reservoirs underneath the mines, has a thickness of only 30 - 40 m near the western boundary of the East German part of the district. The thickness increases gradually to 80 - 100 m at the eastern boundary, and to more than 500 m in the main Zechstein basin (see Fig. I/2-6 for regular bromine profiles of the rock salt sequence).

The South Harz potash mining district was developed since the beginning of this century because of the excellent quality of the Stassfurt potash bed in areas where the original carnallite had been converted locally into high-grade sylvinite, see Fig. I/2-16. Due to their origin, such sylvinite occurrences are limited in their extent.

Some mines soon encountered difficulties in finding high-grade sylvinite; they were abandoned or kept in stand-by condition, see WEAVER (1963) for a summary of the early development.

For various reasons outlined in detail by BAAR (1960), most operating potash mines of the South Harz district ran into difficulties at the beginning of the 1950's: the known sylvinite reserves were nearly exhausted, partly because of manpower shortage during and after World War II; the main reason, however, was the lack of necessary underground exploration.

Exploration efforts were misdirected to drilling from the surface due to misleading geological hypotheses.

Those readers interested in details are referred to maps published by BAAR (1960) and by GIMM (1968, Fig. 2-17 after STOLLE, 1962, and DÖHNER, 1965; for unknown reasons, several potash mines are not shown on this map).

The misleading geological hypotheses (particularly RICHTER-BERNBURG, 1955, pp. 614-618) postulate primary facies differentiations in the Zechstein basin and its sub-basins, including the South Harz basin, to the effect that sylvinite would be found only near the boundaries of the potash deposits; in central areas, the Stassfurt potash bed is assumed to be carnallitic. Such hypotheses are shown erroneous by the actual distribution of high-grade sylvinite in the South Harz district as shown on the maps referred to above.

The maps show local transitions from carnallite to sylvinite and barren zones. In most cases, such alterations are clearly attributable to post-depositional solution processes as shown schematically in Fig. I/2-16. The principal argument is that "gases, if present, are occluded only in what BORCHERT and MUIR (1964) termed 'reaction' minerals", as shown in I/2.2.3, pp. 32-35.

There are, however, other areas in which the conversion of the highly soluble carnallite occurred immediately after the deposition of the Stassfurt potash bed when the brine levels in the South Harz sub-basin rose on account of diluted influxes, see 2.1.2.3.

Along the boundary of the sub-basin, groundwater action had similar effects. However, with one exception dealt with in Chapter 5, the potash mines kept sufficient distances from areas affected by groundwater solutioning.

The potash distribution map referred to above is based on research begun during the early 1940's and continued until 1951 while the potash mining industry was owned by Soviet companies. When the potash mines were handed over to the East German administration, the map was presented to support a proposed underground exploration program (BAAR, 1953b, with discussions). The proposed exploration for sylvinite from existing potash mines was considered necessary to avoid the uneconomic extraction of carnallite as postulated by several writers. After heated discussions, this writer was assigned to direct the proposed exploration.

The underground exploration program proved successful, as shown in detail by STOLLE (in GIMM, 1968, pp. 77-86); the use of bromine contents for stratification of the rock salt sequence, see Fig. I/2-6, proved particularly helpful as no trained geologists were available at that time.

However, the underground exploration program for sylvinite appeared in jeopardy when some emerging rock mechanics "experts" postulated sweeping changes to mine design principles; some details of rather questionable postulates are discussed in 7.2.1.1.

The published controversies during the early 1950's should be viewed against the background outlined in the preceding summary of the development of the South Harz mining district: this writer, having taken the assignment to find sylvinite reserves for the operating mines, had no choice but to show the hypotheses which turned the new sylvinite reserves into barrier pillars, etc., erroneous.

8.2.1.2 A unique case history: potash mine produces oil and natural gas

In 1930, oil started flowing out of developing potash extraction panels of the Volkenroda mine. One of the panels is shown in Fig. 8-1. Similar outflows of smaller amounts of oil and gas occurred in other isolated mined-out panels of the mine. The governmental mine inspectors were stunned; unaware of the dangers posed by explosive gases, several explosions were set off when the panels were inspected using open lights.

The composition of the gases - analyses can be found in GIMM (1968, Table 10/1), and in publications referred to - clearly indicated the origin of the oil and of associated gases and brines: the fluids were stored in suitable geological structures of the dolomite formation underneath the Zechstein 2 salt sequence.

Gases of similar composition had been encountered previously in other potash mines of the South Harz district. However, the oil flow in the Volkenroda mine was the event which triggered oil exploration programs in most existing potash mines. The exploration holes were drilled from the mine workings into the underlying dolomite formation.

At some locations, the anhydrite at the basis of the salt sequence also contained fluids in fracture systems. Fig. I/2-16 shows consequences of tectonic events in the geological past which allowed stored fluids to ascend into overlying formations, and finally to the surface. At most locations, the bulk of hydrocarbons disappeared in this way, so the exploration for oil proved unsuccessful.

However, at the Volkenroda mine, which is connected to the adjacent Pöthen mine by the two-entry system seen on Fig. 8-1, the exploration for oil and gas had some success. Its principal achievement was the removal of oil and gas from structures underneath future potash mining panels; the amounts of utilized hydrocarbons were relatively small. Some statistics (from GIMM, 1968, p. 548) are presented as follows.

At the Volkenroda mine, a total of 242 oil exploration holes were drilled from the potash level, comparing to the 40 holes drilled at the interconnected Pöthen mine.

The holes were drilled at angles of approximately 45° to intersect as many fracture systems underneath the rock salt as possible. 25% of the holes encountered oil and gas, 10% hit brines only, and

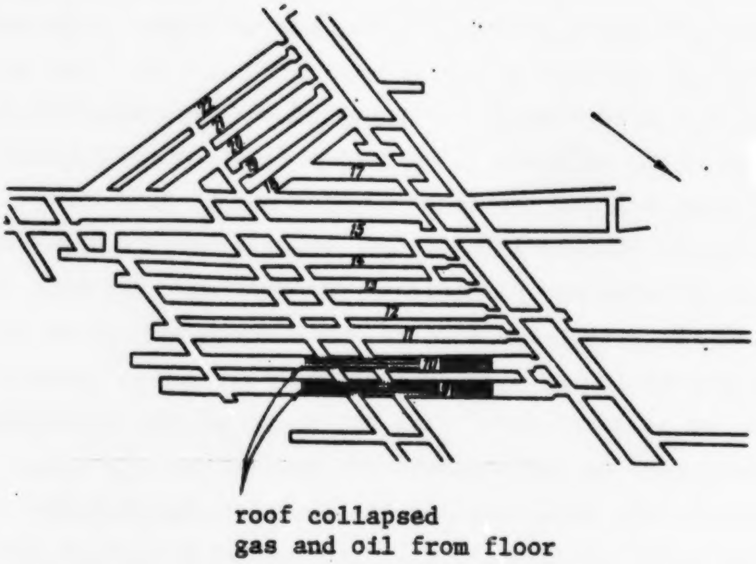


Fig. 8-1 Oil and gas occurrence at a newly opened panel at Volkenroda mine, September 1930 (after BAAR, 1959a, Fig. 1)

the rest remained dry as apparently no fracture systems were intersected.

Frequently the gases were not associated with oil, the structures being occupied by brines under gas caps. The writer is stressing the point that such structures are not connected to groundwater aquifers as such connections would have allowed the gases to escape.

The individual reservoirs were not interconnected since the pressure in each reservoir dropped from the original lithostatic pressure to the atmospheric pressure. The flow rates were governed by the relationships shown in Fig. I/4-15, and in Figs. I/4-17 through I/4-19.

From 1931 - 1938 some 82000 tonnes of oil were recovered; the gas was utilized in the refinery. The writer (l.c., p. 551) emphasizes the observation that oil and gas began flowing out of some holes only after the extraction of the overlying potash bed reached the respective area.

This is an extremely significant observation: in 1951, when the extraction of the potash bed reached areas which had not been included in the oil exploration program during the 1930's, gas released from the floor of an isolated developing potash panel was accidentally ignited; the explosion caused numerous fatalities.

Apparently, the writer failed to recognize the significance of stress relief creep which makes such unexpected release of gas possible.

Such ignoring of proven facts can be extremely dangerous under certain geological conditions; this point must be stressed again as there is definitely no need for mass accidents which are clearly attributable to the application of erroneous hypotheses in the design of potash mines.

8.2.1.3 1930 case history duplicated in 1951

The 1951 methane explosion at the Volkenroda potash mine was possible because of the repetition of the dangerous mine development principles which caused the 1930 events.

Additional mistakes are attributable to the mine management and to the governmental mines inspectorate. The following report represents the literal translation of the report by GIMM (1968, p. 552) who refers to 26 serious gas accidents in potash mines of the South Harz district which claimed 46 lives.

At the Volkenroda mine, the first gas explosion occurred in 1930 as described above; it claimed 3 lives. "Another heavy explosion of oil and gas from floor strata occurred on July 2, 1951, in the interconnected Pöthen mine; at that time, the mined-out rooms were not backfilled as a system for hydraulic backfilling was missing. Mined-out areas of considerable extent were left open. Considerable deformations were in progress as the depth exceeded 1000 m."

"The room in which the explosion was set off had been excavated a long time ago; the floor had been lifted up by 2 m. Gas had accumulated over the weekend; it was ignited by an electrical spark at the beginning of the Monday morning shift. The explosion claimed 9 lives".

The writer fails to mention the practice of shutting down the ventilation system over weekends, and the fact that an atmospheric low pressure system had just reached the area. It is well known that gas accumulated in unaccessible mined-out areas enters the mine workings under such conditions, and the 1951 explosion cannot be blamed at unforseeable rock deformations.

The latter also holds true for another methane explosion which occurred 9 days later at another mine in the South Harz district: a roof fall pushed gas which had accumulated in a mined-out panel into a travel entry where mining crews took their coffee break; the gas was ignited by open light. The explosion killed 12 and injured 22 miners.

At this point it is emphasized that the statistics published by GIMM (1968) and by other writers do not include gas accidents which occurred while most of the potash mines of the South Harz district were used by the military before, during, and after World War II. It is not known if such statistics are available; however, this writer's statement at the end of Chapter I/1 includes a number of serious gas accidents until 1951.

Being reminded of unpleasant duties when discussing such disasters is certainly not a pleasure - however, no matter how many theoreticians dislike being reminded of potential consequences of the application of their erroneous hypotheses, it is this writer's firm belief that those responsible for safe underground operations in salt deposits must be made aware of potential dangers and of mining situations which are known to have caused the emanation of gas into mine workings.

More important, however, for designers of salt and potash mines is the knowledge of how such danger from gas exhalations can be prevented by suitable methods of controlling excessive floor deformations. Intentional roof caving, where suitable, proved most feasible as shown in the following text.

8.2.1.4 Intentional roof caving introduced after decade-long delay

One method of controlling dangerous floor deformations in the potash mines of the South Harz district is the secondary pillar mining dealt with in 7.2.1.1; it requires the redevelopment of areas mined-out in the first phase of extraction and is considered uneconomic unless the following prerequisites are met (GIMM, 1968, p. 378): the pillars considered for extraction should be at least 8 - 10 m high and wide; the K_2O content of the ore should be relatively high.

In most mines the cited prerequisites are not fulfilled as the pillars left during decades of earlier mining are only 5 - 6 m wide - or less in cases where extensive spalling occurred prior to backfilling.

The writer stresses the disadvantage of the common practice of making the pillars ready for backfilling, meaning that the pillar widths were further reduced. This practice had long been recognized as the cause of gas and brine intrusions from the floor of mined-out panels. As a matter of fact, it caused the collapse of a mined-out panel in one of the mines which suffered gas explosions and collapses in 1951(BAAR, 1954a, p. 135).

On the basis of these observations, and of similar observations in roof collapse areas of other mines (BAAR, 1953c), this writer submitted the proposal to use intentional roof caving methods for the total extraction of the sylvinitic Stassfurt potash bed in the South Harz district (BAAR, 1954a, p. 139). It was also demanded that the governmental mines inspectorate retract regulations which made barrier pillars mandatory in all potash mines of the district. Barrier pillars were considered dangerous because of their negative effects on overburden subsidence and floor deformation - not to mention considerable losses in sylvinite reserves which had been established in the underground exploration program under this writer's direction, see 8.2.1.1.

This writer's proposals, officially submitted according to the law of the country, were turned down by representatives of the SPACKELER/GIMM school who were advising the governmental mines inspectorate. An announced publication (BAAR, 1954, p. 139) of the reasons why intentional roof caving methods should be employed was suppressed.

However, 5 years later, GIMM (1959) published similar proposals "after having learned that overburden subsidence cannot be prevented anyway in room-and-pillar mining", as the editor of the respective periodical put it (editorial comments to BAAR, 1959a, l.c., p. 250).

The reasons why the publication was suppressed in 1954 was apparent: hypotheses held by the SPACKELER/GIMM school are shown dangerous when applied in designing extraction methods for potash mines in the South Harz district; the necessity for better control of floor deformations is particularly stressed.

To achieve effective control of floor deformations under the given geological conditions, two methods were proposed:

(1) intentional roof caving with total extraction of sylvinite beds with thicknesses up to 5 m.

(2) total extraction of sylvinite beds with greater thicknesses by secondary pillar mining after proper backfilling, see 7.2.1.1.

In view of the strained sylvinite reserves, the economic advantage of intentional roof caving could be shown as follows: the shale (saliferous clay) overlying the Stassfurt potash bed offers near-ideal possibilities for intentional roof caving; due to intensive fracturing, it is caving when exposed in entries and extraction rooms with relatively small widths.

To prevent its caving, salt beds are left as the roof of openings; 2 m of roof salt were considered sufficient, but JUNGHANS (1952), in a doctoral thesis accepted by the Freiberg Mining Academy, postulated thicknesses of 4 m for the potash mines in the South Harz district. This impractical postulate reflects hypotheses held at that time by the SPACKELER/GIMM school.

This postulate makes no sense for the following reasons outlined by BAAR (1959a, p. 257): in large areas of the South Harz district, the sylvinitic potash bed is only 3 - 5 m thick. It consists of high-grade ore. Even with extraction ratios of approximately 50% in room-and-pillar mining with long pillars, the extraction was economically feasible.

However, increasing the thickness of the roof salt to 4 m would mean increasing the losses in high-grade sylvinite to 75%. Considerable proven reserves with thicknesses up to 5 m would become unextractable.

Under such geological conditions, intentional roof caving methods such as applied successfully for decades in the Alsace mining district of France, offer the best possibility of better use of available high-grade sylvinite reserves.

The reasons are translated and shortened as follows (BAAR 1959a, p.257): due to loosening, caved roof masses require a volume 1.3 - 1.5 times the original volume; depending on its caving characteristics, the roof shale in the South Harz mines may exhibit differences; however, shale thicknesses of approximately 15 m are considered sufficient to provide immediate restraint against floor deformations after caving, provided the thickness of the sylvinite bed does not exceed 4 - 5 m.

The recompaction of the caved shale masses requires loads which are supplied either by floor deformation or by subsiding overburden formations. For this reason, overburden subsidence must be initiated, particularly in the western part of the South Harz district where excessive floor deformations are known to result in gas and/or brine inflows. Intentional roof caving methods are more effective than the traditional room-and-pillar mining with hydraulic backfilling as postulated by the SPACKELER/GIMM school.

Advantages and disadvantages of various roof caving methods considered practicable with the mining equipment available at the beginning of the 1950's were discussed in more detail (BAAR, 1959a, pp. 257/258). These discussions are outdated by modern mining equipment which makes caving methods even more attractive as demonstrated in the Alsace potash mining district of France, see I/4.5.2 and I/5.4.2.

At the beginning of the 1950's, this writer failed to convince the East German theoreticians of the need for intentional roof caving methods in the South Harz district.

Most of the established sylvinite reserves were declared non-extractable or turned into barrier pillars; secondary pillar mining was declared dangerous.

This writer returned his assignment, but made sure that the controversies were published (BAAR, 1959b).

The subsequent development as documented in numerous publications, appears most interesting:

GIMM (1969) allegedly was the first theoretician at the Freiberg Mining Academy to cast doubt on the traditional mining methods which call for the prevention of any subsidence above potash mines.

Evidence from surface subsidence measurements since the beginning of this century, see 7.2.1.1, appears overwhelming indeed. However, one wonders why the SPACKELER/GIMM school kept pretending until the late 1950's that surface subsidence were dangerous, particularly in the South Harz district.

As far as this writer could make out from countless publications by GIMM and his assistants and co-workers at the Freiberg Mining Academy, they never learned why surface subsidence must be initiated.

It has been known for many decades that gas and brine intrusions from the floor do not occur if rocksalt is present in sufficient thickness. Therefore it appears rather strange to credit the discovery of the significance of the salt thickness to GIMM (1969), as is the case in numerous publications, e.g., GIMM and MEYER (1962), see Fig. I/5-13A.

GIMM (1968, p. 398) summarizes his hypotheses on the prevention of dangerous floor deformations as follows (literal translation):

"Three different methods are available:

1. To design the pillars very wide so that the load on the floor rocksalt is kept small; in this way, the dangerous penetration of pillars into the floor can be prevented. However, because of the small

extraction ratios, this method is of little economic interest.

2. To change over to intentional roof caving with yielding pillars. The pillars are left only for a short period of time to reduce the dangerous penetration into the floor. The particular advantage of this method is that the floor deformations become more uniform than those caused by room-and-pillar mining. However, the increased depth of the deformations could be disadvantageous, even dangerous. It is not possible to answer the question if such methods are safer than the present room-and-pillar mining; more comprehensive research is required.

3. To continue the room-and-pillar mining and to reduce the danger of water inflow by reducing the delay time between extraction and backfilling. However, this method allows only relatively small extraction ratios".

These statements make one point apparent: the writer is running in circles, proposing methods which are declared disadvantageous in the next sentence. However, more research is postulated - in the laboratory, of course, because it is convenient and provides fast results for further publications to promote academic careers.

"Nevertheless, intentional roof caving methods are the most economic methods, as they allow the highest extraction ratios. However, the problem of potential water inflow through the floor strata needs further clarification; overburden deformations may also increase and cause additional danger of water inflow through roof strata."

"To date, experience allows the conclusion that the overburden strata will remain impermeable if roof caving methods are applied for the extraction of potash beds with small to medium thicknesses. However, the upper limit of thickness for which roof caving methods are admissible in the South Harz district is still unknown; it must be determined by complex research".

The writer gives no indication of the type of the postulated research. However, he contradicts his own statements (l.c., p. 381) as follows:

"Surface subsidence measurements prove in principle the feasibility of extraction methods with controlled overburden subsidence in mining districts where, according to obsolete hypotheses, only room-and-pillar mining with pillars of sufficient width is considered feasible".

"In view of experience in other potash mining districts, e.g., Carlsbad/New Mexico and Alsace/France, and in view of the economic disadvantages of secondary pillar mining, it is assumed that other methods with high extraction ratios will be used to eliminate the need for secondary pillar mining".

"For example, experimental mining with intentional roof caving was successfully performed in the Volkenroda-Pothen potash mine in 1965. In newly developed mining areas, secondary pillar mining probably is disadvantageous for economic reasons, unless the thickness of the extracted potash bed exceeds approximately 5 m".

The writer (l.c., p. 384) presents yet another version as follows:

"Recently (HÖFER, FULDA, SEIDL, 1965), intentional roof caving which resembles in principle the method used in the Alsace district, is under study at the Volkenroda-Pothen potash mine at depths of 1000 m. Experience to date is good (HÖFER et al., 1967). In the South Harz district, extraction ratios come close to 80%, comparing to approximately 95% in the Alsace district".

However, HÖFER et al. (1967) have the history entirely different. The writers ignore the apparent fact that the roof caving methods introduced in the South Harz district were designed after French experience in the Alsace district. Instead, it is claimed that the design is based on HÖFER's (1968a) research.

In view of the fact that HÖFER (1968b) presented himself as the staunchest theoretician to postulate barrier pillars as abutments for stable stress arches to prevent any overburden subsidence, such claims are astonishing indeed.

In fact, HÖFER et al. (1967) repeat exactly what this writer stated in his official 1954 proposal referred to above. A shortened version reads as follows (translated from HÖFER et al. (1967): l.c., p. 381:) The potash bed mined in the South Harz district is overlain by shale which tends to cave easily. The thickness of the floor rocksalt is significant because the underkying strata contain gases and brines. (l.c., p. 383:) The assumption that rockbursts would occur proved erroneous; measurements justified the expectation of smooth subsidence of the main overburden. Various proposals for the total extraction of the potash bed were made by GIMM (1969), and by NEUBERT (1961, two publications), after HÖFER (1968a) had published his doctoral thesis.

The final proposal is based on an unpublished research report by HÖFER (1962) who designed the intentional roof caving method; large-scale experimental extraction fully confirmed the economic expectations. Intentional roof caving is now being employed in several areas of the Volkenroda-Pöthen mine.
(l.c., p. 387:) At the beginning of the experimental extraction the maximum height was limited to 3.5 m; in the meantime, it was increased to 5m. Extraction ratios of 80-85% are achieved. The traditional slusher haulage was replaced after the rock-mechanical feasibility of the new method had been shown; modern equipment allows full utilization of the economic advantages of the new extraction method. (l.c., p. 388:) The economic success results from the fact that there is no need for leaving thick salt strata to prevent roof collapse, as is the case in traditional room-and-pillar mining with long pillars. With seam thicknesses decreasing to the economic limit of 4 m set by the necessity of leaving high-grade ore in the roof, the extraction ratios decreased sharply. This limit was lowered to approximately 2m, and large areas which had to be left unextracted are now being mined; the economic success is remarkable.

This is an impressive success story indeed. This writer appreciates the publication by HÖFER et al. (1967) for the following reason: when this writer submitted his identical official proposal in 1954 as documented in publications, the laws of the country promised considerable benefits, comparable to patent fees, for innovative methods which were introduced. Accordingly, the government of the German Democratic Republic was asked to settle the account.

8.2.1.5 Measurements

HÖFER et al. (1967, p. 388) present results of measurements made during the experimental mining dealt with in 8.2.1.4. The writers intend to show that, in principle, the deformations developed as expected.

The writers do not indicate what exactly was expected, but refer to hypotheses developed by HÖFER (1968a, 1968b), MICHALZIK (1966), HÖFER and MENZEL (1963), DREYER (1965), and PFORR (1965). These hypotheses, based on misleading laboratory experiments and erroneous theoretical assumptions are discussed in detail in Vol. I.

Expected ultimate pillar strengths are irrelevant anyway in analysing extraction methods with intentional roof caving. The pillars are utilized only for a short period of time, and their sole purpose is to provide safe roof conditions near the advancing extraction front. The pillars are blasted away before any significant reloading after stress relief creep can take place.

The role of pillars in mining methods with intentional roof caving resembles the role of artificial roof support near the advancing extraction front.

It is re-emphasized that stress relief creep immediately after excavation occurs into any newly excavated opening; the creep rates depend on the size of the area from which the original stresses are removed.

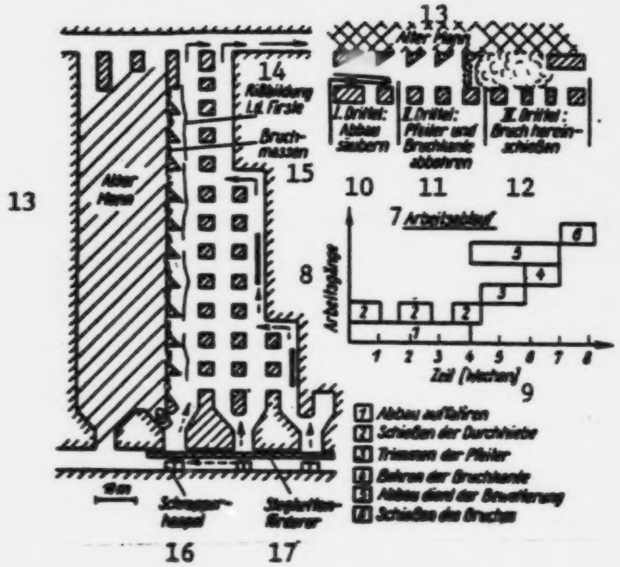
With reference to 7.4.2.2, an important factor in the geological conditions of the case history under discussion is stressed here: floor strata consisting of carnallite exhibit the highest stress relief creep rates.

The roof strata, however, deform elastically, possibly by buckling if dragged into the excavation by horizontal stress relief creep near the face.

As the writers fail to report if clay layers are present near the temporary roof, there is no possibility of assessing the well known effects of such discontinuities.

Thick clay layers cannot be detected on several photographs shown in the article under discussion. However, typical effects of rapid stress relief creep can be seen at least on one photograph (1.c., Fig. 11): curved spalls are separating from the pillar walls inside the "active" cross-section of the opening, see Fig. I/4-3.

The photograph was not taken in the experimental panel referred to in the following discussion; in the experimental panel, see Fig.8-2,



1 development of panel
2 blasting of cross-cuts
3 trimming of pillars
4 drilling the cave line
5 development for ventilation
6 blasting to induce caving
7 work schedule
8 work elements
9 time (weeks)
10 1. third: clean up
11 2. third: drilling of pillar and cave line
12 3. third: blasting to induce caving
13 abandoned workings
14 fracturing of roof
15 caved strata
16 slusher
17 chain conveyor

Fig. 8-2 Experimental panel for investigation of intentional roof caving, South Harz potash district, Germany (after HÖFER et al., 1967, Fig. 8)

the traditional slusher technology was used, while the photograph shows a modern heavy-duty transporter. The writers (l.c., p. 387) report that modern equipment is used in other roof caving panels to increase the daily advance of the extraction front; this means the extraction front is advancing faster into abutment load zones. As the abutment loads increase with the span of the caved area, the effects of stress relief creep (spalling off pillars and floor uplift) also increase.

The writers consider the selected measurement data as the most important results of their rock-mechanical investigations. It must be emphasized here that the measurements were taken in the access entry of the experimental panel shown in Fig. 8-2. This is another reason why there is no basis for comparisons with the measurements dealt with in 7.4.2.2. There are more differences in relevant conditions, such as depth, daily advance of the excavation front, and excavation method (blasting instead of cutting). In addition, some of the presented results of measurements are meaningless; their interpretation in the article under discussion cannot be accepted, as shown in the following detailed discussion.

1) Fig. 8-3 (l.c., Fig. 13) shows roof subsidences measured in the access entry to the experimental panel, Fig. 8-2.

The writers fail to provide information on possible previous extraction mining in surrounding areas, so it is not known if they refer to virgin ground conditions, or to conditions under which the original overburden load of approximately 250 kp/cm^2 might be increased, possibly to twice the original value, or to even higher values if the entry is located in overlapping abutment zones.

Furthermore, the entry does not reflect the development of deformations in the caved panel from which it is separated by large pillars, see Fig. 8-2. Apparently, these pillars were left along the entry, representing a part of the abutment zone which develops when the panel is extracted. Consequently, the initial deformations seen in Fig. 8-3 reflect mainly the re-activation of stress-relief creep due to excavation of the panel entries. This interpretation applies to the roof subsidences measured at the MP's (measuring points) 10 through 7 on 22.11.1964.

As the writers fail to indicate the date of the first measurements

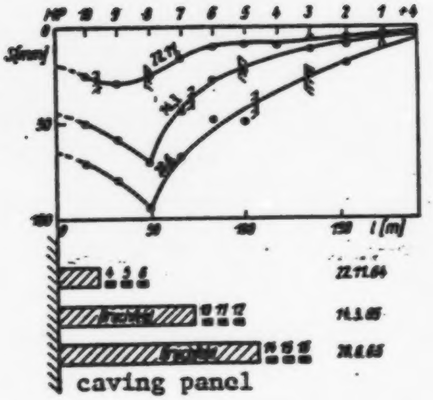


Fig. 8-3 Experimental panel: roof subsidence (S) at measuring points (MP) along the access entry to the experimental panel, measured on November 11, 1964, March 14, 1965 and June 20, 1965 (after HÖFER et al., 1967, Fig. 13)

and the development of the roof subsidences at each individual MP, no rational interpretation of the apparent underground subsidence trough is possible. In addition to stress relief creep, reloading creep due to widening of the panel may have occurred.

The first subsidences measured at MP's 6 through 1 definitely do not indicate overburden subsidences in advance of the extraction front as the writers theorize (l.c., p. 388); these subsidences reflect the creep due to the build-up of abutment loads around the developing caved panel, i.e., horizontal creep into the entry. The measured total underground subsidences show a linear decrease from MP6 to MP 1, giving an indication of the approximate width of the abutment zone ahead of the advancing extraction front on 22.11.1964. At this date, the span of the panel, including the caved area and the next 3 entries, was 50 m, while the width of the abutment zone was at least 100 m; a better estimate is not possible as the underground subsidences measured at greater distances from the advancing extraction front are not indicated.

The second underground subsidence curve, measured on 14.3.1965, shows no increase in the width of the abutment zone ahead of the extraction front. However, the first and the second curve diverge towards the extraction front, and further to the centreline of the partly or completely extracted area, showing the abutment loads increasing with decreasing distances from the developing panel.

It must be borne in mind that the entry in which the measurements were taken is located in the abutment zone of the developing panel. The distance between the entry and the panel does not change. For this reason, the distances between the two first curves cannot change to the extent shown at MP 8 if abutment loads are the only cause of increased underground subsidences.

This applies particularly to the sharp increase at MP 8 between the first and the second measurement; some of it is attributable to re-activated stress relief creep as the zone in which the panel entries were excavated passed along MP's 8 through 6. MP 8 indicates an irregular development which could have several causes, including local bed separation, local loosening of the roof due to fractures, or merely damage done by mining equipment; apparently, MP4 was completely lost during this period of measurements. Just one error in reading the precise level could also result in the irregularity at MP 8.

It is emphasized that the third curve, measured on 20.6.1965, runs virtually parallel to the second curve, indicating continuing increases in abutment loads along the boundary of the panel. MP's 3 through 1 indicate the same for the front abutment.

Elimination of the apparently irregular reading at MP 8 results in underground subsidence curves which show the characteristics of Fig. 7-1, and of the curves shown in Fig. 6-11. As a matter of fact, the measurements for Fig. 5-11 were taken in a potash mine with very similar geological conditions; the collapse of several pillars caused similar rock-mechanical conditions.

In other words: Fig. 8-3 confirms relationships which have been known for some time and represent one reason why roof caving methods should be used to ensure effective control of floor deformations in the South Harz district.

2) It must be stressed that the lengths of the time periods between the measurements shown in Fig. 8-3 are unequal, so the distances between the curves are not indicative of the underground subsidence rates. HÖFER et al. (1967, p. 388) report convergence measurements taken in the panel access entry over a total of 389 days; it appears justified to assume that the subsidence measurements were taken over the same period of time. If this assumption is correct, the lengths of the time periods between the measurements for the three curves of Fig. 8-3 calculate as 179 days for the first curve, 112 days for the second curve, and 98 days for third curve.

Approximate underground roof subsidence rates, calculated from these time intervals, and the actual subsidences shown in Fig. 8-3, may be compared for the MP's 9 and 8; these two points are located near the centreline of the developing caved panel. MP 9 is located at the fourth panel entry, MP 8 at the sixth entry, the distance between the two points is approximately 20 m.

The subsidence rate at MP 9 increases slightly during the second interval, and remains more or less constant.

At MP 8, the subsidence rate as calculated from Fig. 8-3 increases sharply during the second interval, and drops back to the values for MP 9 during the third interval. This development cannot be reconciled with normal subsidence characteristics, as emphasized before. HÖFER et al. (1967) should have eliminated the apparent error in Fig. 8-3, or else they should have provided a plausible explanation of the irregularity when publishing the figure.

3) HÖFER et al. (1967, p. 388) incorrectly assume overburden subsidence ahead of the advancing extraction front, as already criticized previously. Their assumption is based on convergence measurements in the panel access entry as mentioned above; it is in need of more corrections to be shown in the following discussion of the reported convergence rates. It appears necessary to provide a literal translation, and a point-by-point correction (in brackets).

"Fig. 8-3 shows underground subsidences ahead of the extraction front reaching the value of 25 mm at the panel boundary; the regular deflection line reaches the maximum of nearly 100 mm in the goaf". (Apparently, the writers refer to the third curve of Fig. 8-3., constructed from measurements taken on 20.06.1965. The measurements were taken in the panel access entry over the distance of 200 m, which is also the final length of the caved panel; the span of the panel was 100 m, see Fig. 8-2. The maximum deflection of nearly 100 mm was measured at MP 8; this point is not located in the goaf, but in the abutment zone of the caved area, as stressed under 1) above. The roof subsidence shown for this point is irregular as shown under 1) and 2) above).

"Along with the measurements of roof subsidence, measurements of floor uplift were taken; floor heave exceeded roof subsidence. On 20.06.1965, i.e., after 289 days, the resulting convergences (of the entry!!) amounted to the following values:
105 mm at MP 5, 197 mm at MP 7, and the extra-ordinary value of 307 mm at MP8. Floor uplifts at the boundary of the panel were more than twice as high as the roof subsidences at some points" (The measurements were not taken at the boundary of the panel, but rather in the abutment zone of the panel; large pillars were left between the panel access entry and the caved area, see Fig. 8-2).

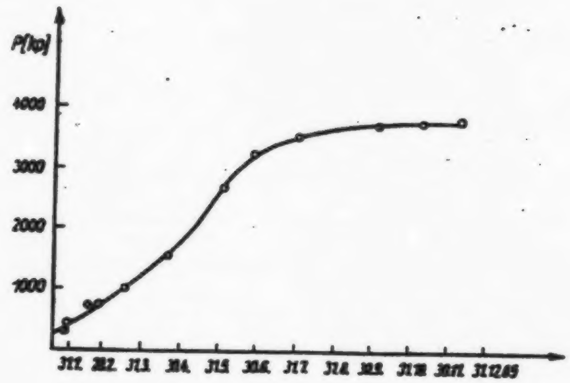


Fig. 8-4 Increase of pressure versus time in the fifth room of the caved-in part of the experimental panel (after HÖFER et al., 1967, Fig. 14)

"However, the initial floor uplift changed to floor subsidence in time, starting at MP 10; this allows the conclusion that the main overburden was subsiding, resulting in floor loading in the goaf". (It is re-emphasized that MP 10 is located in the access entry; so are all other MP's located in the abutment zone of the caved panel. Apparently, the writers admit initial abutment loads as cause of the initial floor heave as they ignore stress relief creep. Needless to say that floor loading in the extracted panel due to subsidence of the main overburden must result in reduction of the abutment loads, i.e., in decreasing deformation rates in abutment zones. The measurement results show the opposite, particularly for the front abutment, as shown under 1) above.

The shift from floor uplift to subsidence in the panel access entry is attributable to lateral creep of the floor salt sequence out of the abutment zone into the excavated area; the creep rates increase as the abutment loads increase, i.e., in time according to time required for the extraction of the panel.

It is definitely inconceivable to assume main overburden subsidence when the maximum span of a mined-out area at the depth of 1000 m is limited to 100 m; this is unambiguously shown by the surface subsidence measurements presented in 7.2.1.1, and particularly by the comprehensive measurements summarized in Fig. I/5-13A, for comparable conditions).

4) HÖFER et al. (1967, pp.387,388) present Fig. 8-4 to show "that the main overburden did subside; there is no danger of a rockburst".

The latter statement is appreciated as it fully confirms this writers position in the published dispute over the danger of rockbursts in the South Harz district which began after disastrous gas explosions in 1951, see 7.2.1.1 and 8.1.2; apparently, the senior writer (HÖFER) changed his hypotheses to the opposite, although references to his first publications which emphasize the danger of rockbursts continue as outlined at the beginning of this sub-section.

HÖFER et al. (1967) conclude from Fig. 8-4 "since the middle of May 1966 the Bunter Sandstone (main overburden) is subsiding".

This conclusion cannot be accepted. In fact, Fig. 8-4 suggests the contrary: continuing floor heave caused by continuing creep out of the abutment zone of the developing panel according to Figs. I/8-1 and I/5-13A. This is shown in the following detailed discussion.

Fig. 8-4 shows the pressure increase in a pressure cell positioned at the distance of approximately 40 m from the stationary boundary of the caved panel. The cell was installed in the fifth room of the panel, i.e., in the first room excavated through the third entry of Fig. 8-2. According to Fig. 8-3, the room was excavated before 22.11.1964, at which time 25 mm of roof subsidence were measured in the access entry at MP 9.

According to the time schedule given by HÖFER et al. (1967, Fig. 8), the intentional caving to load the pressure cell was introduced one or two weeks after the installation of the cell, i.e., at the beginning of December 1964. For unknown reasons, the exact time of caving is not indicated on Fig. I/8-5; the time scale begins in the second half of January 1965, i.e., at least one month after the intentional caving. At the time of the first pressure readings plotted on Fig. 8-4, the span of the caved area measured considerably less than 75 m which was the span on 14.3.1965, see Fig. 8-3 ; so the actual span at the time of the first readings was approximately 50 m.

It has been documented repeatedly that caving of the roof shale does not affect the overlying anhydrite if the span of the caved area does not exceed approximately 50 m (BAAR, 1953c, Figs. 8 and 9, with detailed discussions by SPACKELER, LEVI, JUNGHANS, BUCHHEIM (1954a; 1958; 1959a), WILKENING, 1958); the reader is referred to 5.3.2, particularly to Fig. 5-11.

At spans including the maximum span of 100 m of the panel under discussion, the mechanism shown in Fig. I/5-13A is effective: lateral creep of floor salt rocks causes floor uplift which in turn causes recompaction of overlying caved roof masses. Lateral creep also increases the pressure of load cells positioned under the broken roof rock.

HÖFER et al. (l.c., p. 388) are quantifying the pressure increase shown in Fig. 8-4 as follows: after the intentional caving, the load on the pressure cell increased almost linearly to 3200 kp/cm^2; then the curve levels off, reaching approximately 4000 kp/cm^2. The calculated load represents the deadweight of approximately 200 m of overburden.

Such quantifications are incorrect for the case under discussion - in contrast to similar measurements presented in 7.4.2.2; the reasons are outlined as follows.

In the case of the measurements shown in Fig. 7-25, the broken rock masses consist of carnallite which deforms very easily by creep, resulting in near-hydrostatic stress conditions around the pressure cell.

In the case of Fig. 8-4, the caved roof masses consist of shale and anhydrite fragments of various sizes and shapes. This is known from observations on hundreds of roof falls; it is also apparent from a photograph shown by HÖFER et al. (1967, Fig. 9). These rock fragments are not deformed when reloading begins; the load acting on the pressure cell depends on the size of the overlying rock fragments. If large fragments are involved, the load on the pressure cell may exceed many times the so-called specific load in kp/cm^2 calculated from the size of the pressure cell.

It is common knowledge that so-called specific overburden loads cannot be calculated from loads on a single prop; as the loading condition of a pressure cell under rock fragments of unknown size is similar, the calculation of so-called specific loads from the pressure cell loads shown in Fig. 8-4 makes no sense.

The writers (l.c., p. 388) calculate the so-called specific overburden load of 50 kp/cm^2 from the last indicated load of 4000 kp/cm^2 of Fig. 8-4. The actual specific load probably was much smaller for reasons given above. Most writers dealing with load cell measurements emphasize that such cells can only provide a qualitative indication of increasing load, see 3.8.1 for details.

Based on the reasons given above, the following re-interpretation of Fig. 8-4 is presented: the pressure cell was loaded by floor heave due to creep of saltrock out of the abutment zones of the developing panel; such creep is known to be a slow process, depending heavily on time, so it took over a month until the first reaction of the cell could be registered.

The increase in cell pressure over the following five months reflects the increase in abutment loads around the developing panel. As the distance to the extraction front increased, and the pressure cell was positioned near the stationary boundary of the panel where the increase in abutment loads was levelling off, the creep rate also levelled off to the final constant, but small rate reflected by the cell pressures registered during the second half of 1965.

However, the increase in cell pressures to 3200 kp/cm^2 is definitely not "nearly linear" during the last month. On the contrary, the correct plot of the pressure readings gives an entirely different type of curve, showing a sudden increase in pressure sometimes in May 1965. Over the following 3 months, the curve develops very regularly into a perfectly straight line which indicates pressure increases at a constant rate. The curve resembles exactly numerous creep curves measured in situ, and presented in CHAPTERS I/3-5, particularly in Fig. I/5-2 (curves marked R, indicating the begin of reloading after the initial stress relief creep had levelled off to creep at constant rates represented by straight lines).

The sudden increase in load in May 1965 is interpreted as caused by sudden subsidence of a block of the overlying Main Anhydrite which is known to have suffered extensive fracturing, see Fig. 2-20. Sudden slippage of anhydrite blocks frequently occurs at the beginning of overburden subsidence and may result in what have been called "small rockbursts"; such slippage causes the sudden increase in loads on pillars, and, of course, on broken masses of shale in the case under discussion. It is not possible to predict when such loading may occur as it depends on the unknown location of fractures in the Main Anhydrite, and on the increase in span of the mined-out panel which causes tension in the deflecting anhydrite plate.

Sudden increases in loads on broken shale masses could not result in a typical creep curve after the event which caused the additional load in May 1965. Here is the explanation based on the assumption that sudden subsidence of a block of Main Anhydrite removed the restraint against stress relief creep in the overlying rock salt sequence. Stress relief creep resulted in reloading of the sunken anhydrite block. As stress relief creep rates are known to decrease regularly, the reloading of a sunken block of Main Anhydrite, transferred through the broken roof rock masses to the floor of the panel and to the pressure cell, also must exhibit rates which decrease in time. That is exactly what the measurements indicate.

In conclusion, it is stressed that the measurement data selected by HÖFER et al. (1967) give no reason for changing a set of erroneous hypotheses to the opposite extreme which is equally erroneous: at least until 1960, leading East German theoreticians, e.g., SPACKELER et al. (1960), postulated that the overburden of the potash beds, including the 100-m rocksalt sequence, be considered as elastic plates which should be supported premanently to prevent any subsidence, rockbursts, groundwater inflow, etc.; only a few years later, it is postulated that the same overburden strata subside rapidly when the span of a mined-out area reaches only about 50 m, comparing to the overburden thickness of 1000 m. Such fast reaction would be comparable to the behavior of unconsolidated rocks dealt with in soil mechanics.

The necessity of recognizing the actual in-situ behavior of salt rocks, particularly the significance of stress relief creep into any new excavation in salt deposits, is re-emphasized. Stress relief creep is most significant under the geological conditions in the South Harz mining district; it was instrumental in mass accidents as shown previously. Apparently, HÖFER et al. (1967) failed to grasp the rock-mechanical reasons why intentional roof caving can be utilized for necessary control of floor deformations.

8.2.2 Roof caving methods in other potash mining districts

The necessity of effective control of floor deformations is not the reason why mining methods with intentional roof caving are applied in other potash mining districts.

The use of such methods in the Alsace potash mining district of France and in the Esparza potash mine of Spain is based on other considerations; particularly the fact that the ore reserves are limited led to the introduction of roof caving methods in the Alsace district.

The extracted potash beds are limited in thickness, and the overburden formations cause no problems in subsidence control, see 7.4. The extraction methods resemble those applied in coal mining. The application of various excavation methods in the Alsace district apparently did not cause serious floor control problems. Occasional gas blow-outs, see Fig. I/4-16, are relatively easily prevented by drilling relief holes into the floor.

There appears no need for descriptions of the extraction methods in this text which is designed to deal with rock-mechanical problems. The reader is referred to mining engineering textbooks; apparently, GIMM (1968) devoted extensive studies to the excavation methods used in the Alsace district, presenting numerous maps which can easily be read even by those not in command of German. The design of intentional roof caving methods in the South Harz district of East Germany dealt with in the preceding is based on French experience over many decades.

Fortunately, the proposal by SERATA (1968) to introduce total extraction methods, as dealt with in 8.2.1, in Canadian potash mining could not be realized because the prerequisites of intentional roof caving methods are not present. According to the writer, "the current practice in Saskatchewan potash mining in determining the extraction ratio is not based on scientific grounds"; this statement is amazing indeed as the IMC mines near Esterhazy, Saskatchewan, were the only potash mining operations in full production at the time of publication as shown in detail in various figures; the original IMC design was based on laboratory research by SERATA.

Apparently, SERATA's (1968) premature proposal was triggered by personal information from East German sources; this follows from the following reasons given in his publication.

"There are two extreme possibilities in regard to the extraction rate of Saskatchewan potash mining. These two extreme situations are found in German potash mining today. More than 20 examples of mine flooding through the overburden have been reported. On the other hand, the extraction rate of up to 92.6% is now practised in one mine at the depth of 3,600 ft".

The writer apparently refers to the experimental mining dealt with in 8.2.1; he arrives at the conclusion that "mining of potash ore below 3600 ft may not only be feasible but possibly advantageous in regard to mine floowing, total extraction and security of mine roof".

As stated above, it appears fortunate that intentional roof caving cannot be used in Saskatchewan potash mining because of the lack of suitable roof strata; had such methods been attempted, the resulting roof deformations would have been disastrous as there is a water-bearing dolomite formation present at distances of approximately 20 - 50 m above the mining levels, as repeatedly emphasized by SERATA in numerous other publications.

However, effective control of floor deformations is necessary when potash beds are extracted above reef structures; to date, this is not the case as such structures can be defined by geophysical methods from the surface, see CHAPTER 6. It is hoped that the vast reserves will ensure that such risky extraction methods are not applied for many decades to come.

8.3 BACKFILLING FOR CONTROL OF FLOOR DEFORMATIONS

Backfilling extracted room-and-pillar potash panels with refinery waste has been for many decades, and still is a much praised method believed to provide effective control of floor deformations, particularly in the South Harz district of Germany where excessive floor deformations are dangerous as shown in 8.2.1. In fact, however, backfilling with hot refinery waste is extremely dangerous.

After the disasters in 1951, see 8.2.1, the erroneous belief in hydraulic backfilling as suitable method to prevent floor deformations lead to several attempts of total extraction of the Stassfurt potash bed under geological conditions which allow complete backfilling of the excavated space immediately after each step of excavation. Such methods were used in anticlinal structures; modified longwall mining techniques had the face advancing towards the crest of anticlines.

One such attempt was made in the Königshall-Hindenburg mine, see Fig. I/5-10 for a cross-section which shows the geological situation. The attempt failed because of unexpected floor deformations documented in detail by WILKENING (1958). It may be emphasized that the flooding of the mine in 1957 was not caused by the total extraction of the Stassfurt potash bed of considerable thickness, but by backfilling of a room-and-pillar panel, see Figs. I/5-11 through I/5-13B.

The total extraction with immediate backfilling after the face advanced resulted in rock-mechanical difficulties which increased with each step of widening the panel. The large-scale deformations were continuously monitored as reported by WILKENING (1958); readers interested in details are referred to the reference publication.

The floor deformations, with bed separations opening and closing, were not of great concern in this particular case as rock salt with sufficient thickness was known to be present underneath the extracted area. Serious problems were caused by roof falls which apparently extended through the roof shales to the bottom of the overlying Main Anhydrite, see Fig. I/2-19 for approximate thicknesses and a scheme of the assumed mechanism of overburden load transfer. Creep deformations of the salt rocks out of the front abutment zone of the advancing extraction front are considered as the cause of the roof falls. Such creep was enhanced by increased temperatures as the refinery waste was still hot when transported hydraulically through pipelines into the excavations.

The method of extraction made it necessary to backfill the excavated opening completely after each step of extraction; the top of the backfill served as floor during the following step of excavation. The refinery waste, consisting mainly of rocksalt and anhydrite, is known to crystallize to a solid rock mass when the brines drain off. There were no problems in this regard; the top of the backfill provided the smooth floor as expected.

However, too much of stress relief creep occurred during each step of excavation. The solidification of the waste may eventually have stopped further stress relief creep, but the stress-relieved floor rocksalt was not recompressed. As a result, considerable abutment loads developed around the extracted area, increasing with each subsequent step of extraction.

Effects of stress relief creep, particularly heavy spalling, increased accordingly, resulting eventually in roof caving before the excavated slice could be backfilled.

Measurements (WILKENING, 1958) and additional wire-extensometer measurements by this writer in boreholes drilled from the main haulage way up to the floor of the total extraction area confirmed that no recompression of the stress-relieved rocksalt in the floor occurred. Only bed separation voids which had opened near the floor of the mined-out slice closed when the opening was backfilled, indicating the most important effect of the backfilling with hot refinery waste: the re-activation of creep when the hot refinery waste caused temperature increase of the rocks around the openings.

Similar effects - re-activated creep of pillars embedded in refinery waste, see Figs. I/5-12 through I/5-13B - resulted in the flooding of the mine in 1957; other mistakes accelerated the flooding.

In view of these published measurements and observations, the reader is cautioned against publications which continue to postulate positive effects of backfilling with refinery waste, e.g., GIMM (1968, p. 371), DREYER (1974, p. 123).

As the increase in temperature causes the deterioration of the supporting capacity of mine pillars, by special caution is necessary in the design of atomic waste repositories in salt deposits.